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Using Carrying Capacity as a Baseline for Building Sustainability Assessment

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USING CARRYING CAPACITY AS A BASELINE FOR BUILDING SUSTAINABILITY ASSESSMENT

by

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Abstract

Bendewald, Michael J. (M.S. Civil Engineering)

Using Carrying Capacity as a Baseline for Building Sustainability Assessment

Thesis directed by Professor John Zhai

This thesis critically reviews existing building environmental assessment methods and provides a computational model that can help address some of their shortcomings. Since building environmental assessment methods are having a huge impact on the way buildings are valued, it is increasingly important that the methods appropriately assess building sustainability. Many critics of the assessment methods argue that the methods should evolve toward an "absolute" assessment of sustainability. That is, rather than assessing a building relative to a typical building, the assessment should be made to whatever is deemed sustainable. One possible form of absolute assessment is using the indicator of sustainability known as carrying capacity. After discussing the opportunities presented with a carrying-capacity-based assessment of buildings, this thesis proposes a computational model that provides such an assessment.

There are four main components to the presented computational model. The first is the amount of carbon (C) stored on the building site in its native state. This native-site carbon storage is defined as the baseline carbon-storage value, and thus represents the carrying capacity of the building project. The second is land use change, which accounts for the removal or addition of vegetation and other carbon storing elements to the project site. The third and fourth carbon emissions sources in the model are building construction and operation.

A building is considered sustainable in the model if by the end of its expected lifetime the total amount of carbon emissions are completely offset. Building designers and their clients can use this model to more comprehensively account for carbon emissions and identify options for reducing

and offsetting them. To promote greater adoption, the model has been developed into an online resource, named Green Footstep (www.greenfootstep.org).

To demonstrate the usefulness of the model, this thesis presents a case study of an institutional building in Lake Placid, Florida. The case study shows that the design team used the model to better understand what it means to have a "low carbon" goal. The model showed them that over one hundred years, the building project must reduce and offset carbon emissions at a rate of 16 tonnes C per year.

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Chapter 1: Introduction and overview

> Society…long ago committed itself to forge ahead full bore with scientific and technological advance, but never to forge ahead in developing the critical self-reflection such change seems to require.
>
> - Langdon Winner
>
> *The Whale and the Reactor* (1987)

> We can't solve problems by using the same kind of thinking we used when we created them.
>
> - Albert Einstein

The concept of physical limits to societal development was first scientifically identified in 1972. The landmark book *The Limits to Growth* assessed the current state of resources use, compared it to the availability of those resources, and attempted to predict the future given our current course. After a harsh popular backlash against limits to societal growth, few if any such studies were done in the following two decades. However, with the rise of greater awareness around sustainability issues, various sustainability indicators that "indicate" limits to growth have emerged, such as The Natural Step framework and Ecological Footprint Assessment.[1] Around this same time, green building rating systems were created.

Despite being roughly the same age in development, green building rating systems are far different from sustainability indicators in that they make relative comparisons between buildings rather than a more absolute assessment that is made with regard to physical limits to growth. With the market success of systems such as BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design) should come greater scrutiny about their effectiveness.

[1] www.naturalstep.org, www.footprintnetwork.org

The academic field that has formed around green building rating systems, also known as building environmental assessment methods, is pushing them toward a watershed in development: from the verification of green buildings to an assessment of sustainability. A sustainability assessment not only considers a wider spectrum of issues, but also represents a fundamental change in the way we view buildings (Kaatz et al 2006). No longer are we attempting to mitigate the environmental impact of buildings, we are assessing how well they restore the ecosystem and contribute to greater societal well being.

This thesis critically reviews existing building environmental assessment methods and provides a computational model to inform their development. Chapter 2 introduces the concept of carrying capacity, which is shown to be not only a necessary element to sustainable development but also provides opportunities for building environmental assessment. Chapter 3 critically reviews building environmental assessment methods and discusses their shortcomings. Chapter 3 then identifies life cycle assessment (LCA) as an emerging methodology within assessment methods and discusses other recently proposed methods for building environmental assessment. Chapter 4 turns to an in-depth introduction of a particular form of LCA known as Economic Input-Output LCA (EIO LCA). A hybrid LCA method is proposed to more accurately assess the embodied energy and carbon emissions of buildings. Chapter 5 presents a computational model that could help building environmental assessment methods capture some of the opportunities discussed in Chapter 2 and address the shortcomings that were discussed in Chapter 3. Finally, Chapter 6 provides a summary of key thesis contributions and presents recommendations for building environmental assessment methods, government policy, and future research.

Chapter 2: Exposition of carrying capacity

The sustainable development initiative has provided the motivation for both sustainability indicators and building environmental assessment methods. The first section of this chapter provides an overview of sustainable development and identifies carrying capacity as a central concept. The following section defines carrying capacity and discusses the lack of its explicit presence in the mainstream sustainability conversation. The final section discusses further this apparent societal resistance to carrying capacity and describes its potentially empowering effect.

2.1 Overview of sustainable development

Sustainability has been defined in more than one way. Definitions include recognizing and meeting the needs of everyone; more efficient use of natural resources; and stable levels of economic growth (Chambers et al 2000). The Latin *sustinere* is to hold, grasp, have, keep (*tinere*) from below (*sus)*. Something sustainable is supported in a way that extends and stretches (*tendere*) into time. The process of creating sustainability, or sustainable development, has been most famously defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (*Our Common Future* 1987).

Rachel Carson's *A Silent Spring* (1962) provided a seminal critique of technological development and, at least in the US, created the intellectual framework necessary for the sustainable development initiative to grow. She showed how a particular technological artifact – the use of DDT – that seemed to be helpful for society was in fact eventually harmful. This caused consternation among her industrial age contemporaries who typically believed technology was a good, in and of itself. By casting doubt on this assumption, Carson gave rise to examination of technology beyond its immediate benefits. Scientists and activists began considering the unintended consequences associated with technological development in both the near- and long-term. The ensuing environmental movement of the 1960s led to the creation of the US Environmental Protection Agency (EPA) in 1970. The EPA was deemed with the task of cleaning up America's cities and former toxic waste dumps (which were often located in the same place). While reversing environmental damage continues to be a strong focus of the EPA, the agency is becoming increasingly focused on prevention. In the early 1990s the agency partnered with businesses to explore voluntary preventive approaches, including the Energy Star building-labeling program.[1] This shift in attention may be attributable to the new global initiative at the time called sustainable development.

The 1992 International Earth Summit at Rio de Janeiro was an unprecedented venue for governments to "rethink economic development."[2] Brought about by a concern for global warming and social inequity, this conference led to the adoption by organizations and governments of Agenda 21, a wide-ranging action plan for sustainable development. This plan was strongly reaffirmed in 2002 at the World Summit on Sustainable Development held in Johannesburg, South Africa.[3] Agenda 21 provides a philosophical framework for viewing development as well as a mix of implementation strategies. It states that:

> We are confronted with a perpetuation of disparities between and within nations, a worsening of poverty, hunger, ill health and illiteracy, and the continuing deterioration of the ecosystems on which we depend for our well-being. However, integration of environment and development concerns and greater attention to them will lead to the fulfillment of basic needs, improved living standards for all, better protected and managed ecosystems and a safer, more prosperous future.

[1] www.epa.gov
[2] Earth Summit: UN Conference on Environment and Development (1992) http://www.un.org/geninfo/bp/enviro.html
[3] UN Department of Economic and Social Affairs, Division for Sustainable Development—Agenda 21 http://www.un.org/esa/sustdev/documents/agenda21/index.htm

UN Department of Economic and Social Affairs, Agenda 21, Preamble

The document identifies scientific research as a main form of implementation. It claims that implementation of sustainability strategies will depend on:

> a better understanding of land, oceans, atmosphere and their interlocking water, nutrient and biogeochemical cycles and energy flows which all form part of the Earth system. This is essential if a more accurate estimate is to be provided of the *carrying capacity* of the planet Earth and of its resilience under the many stresses placed upon it by human activities.

Agenda 21: Chapter 35

(emphasis added)

The authors of Agenda 21 explicitly recognize that sustainable development requires an approach that integrates economic, equity, and environment concerns. These members of the United Nations claim that an estimate of carrying capacity is not sufficient to sustainability, in that it is the only concern, but it is necessary. In this way it is one form, and one point of reference, in the seeming archipelago of sustainable development.

2.2 The Green Revolution: Liberty, Equality, Fraternity, *Capacity*

2.2.1 Definition of Carrying Capacity

Carrying capacity is "the ability of the earth to support life" (Chambers et al 2000 p. 46). Carrying capacity had been a term used by biologists to describe how many animals a given habitat could support, but only recently is the concept being applied to humans (Chambers et al 2000). Human carrying capacity is understood as the provision of ecosystem services, such as climate regulation and growth of food and fiber.

Ecosystem services contribute to the well being of human beings. Inherently difficult to acknowledge in our socio-technical milieu, ecosystem services have been identified in various ways. In 1996, Wackernagel and Rees introduced Ecological Footprint Assessment (EFA) to identify in terms of land area the ecosystem services we use. In 1998, the net worth of ecosystem services used in the global economy was estimated to be an average US$33 trillion (Costanza et al, 1998). In 2000, the Ecosystem Millennium Assessment was formed by the United Nations to define ecosystem services in terms of human well being.

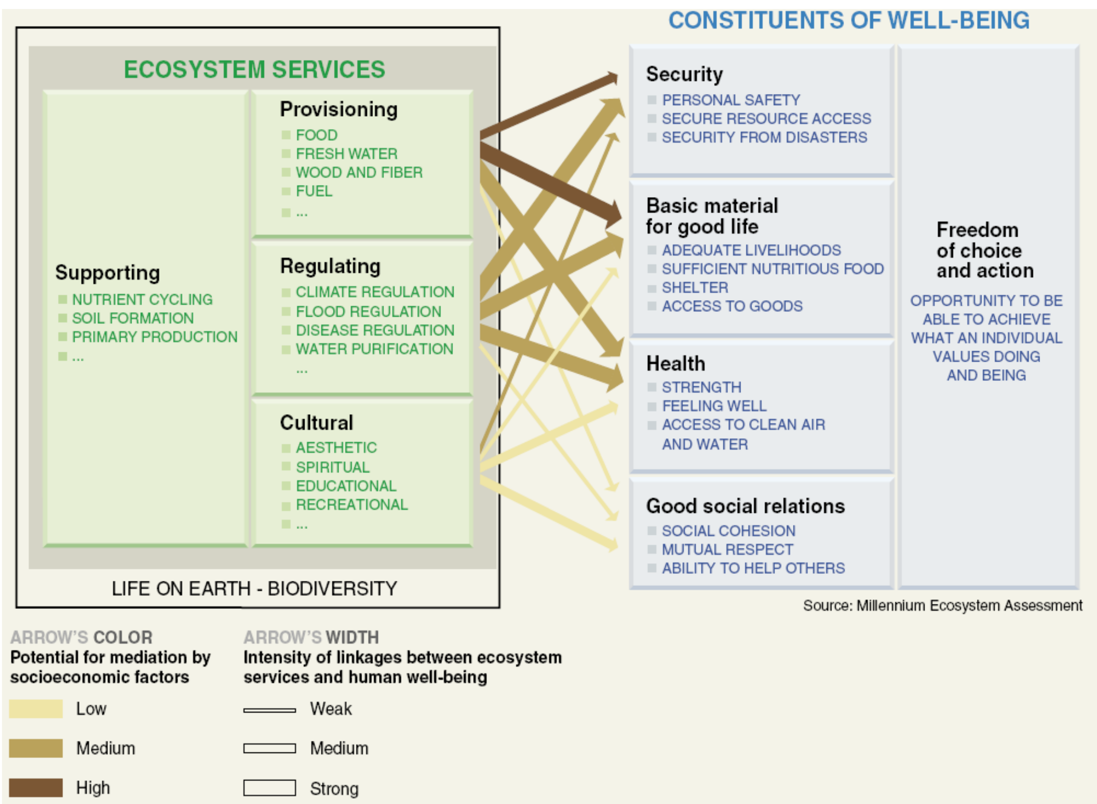

Table 2-1. Ecosystem Millennium Assessment chart of ecosystem services.

Unlike Costanza et al (1998) and the Ecosystem Millennium Assessment, EFA estimates not only the amount of ecosystem services we use but also the amount we could theoretically use given current technological practices. EFA finds that this theoretical rate of ecosystem services regeneration is actually *less* than the rate at which we consume and create waste. This over-exploitation and excessive waste generation eventually leads to the loss of these services permanently, as evidenced by desertification, deforestation, soil oxidation, fishery collapse, loss of biodiversity, ozone depletion, and global warming (Wackernagal and Rees 1996). EFA calls this apparent extension beyond carrying capacity "overshoot."

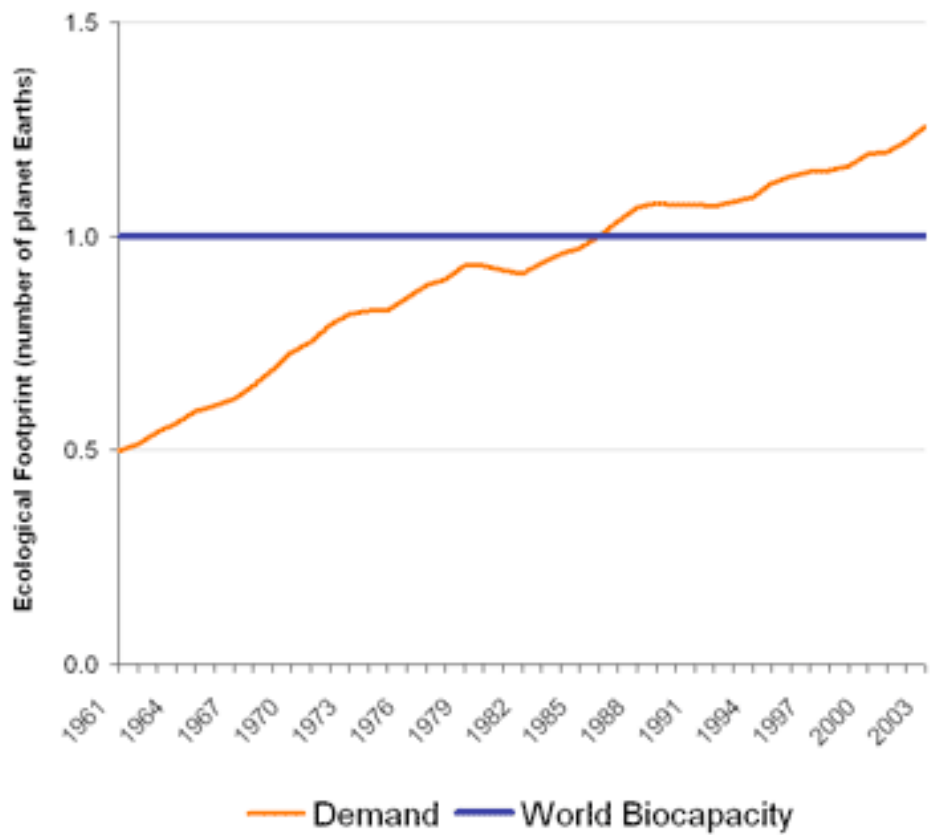

Table 2-2. Estimate of consumption of ecosystem services ("Demand") with regard to global carrying capacity. According to EFA, we are currently using about 1.3 planet Earths. (www.footprintnetwork.org)

2.2.2 Resistance to Carrying Capacity

Despite accelerated interest in ecological footprinting, ecological economics, and other frameworks that make carrying capacity explicit, the popular discussion of sustainability is focused on targets for reduction of pollution. The two types of assessments are very different: a carrying capacity assessment is made with regard to whatever is believed to be the sustainable solution; a target-for-reduction assessment is made with regard to whatever is conventional.

The Nobel Prize Laureate Intergovernmental Panel on Climate Change (IPCC) has made important strides toward revealing solutions to global warming yet never mentions carrying capacity (IPCC 2007). Instead of living within carrying capacity, the IPCC target is to 1990 levels of carbon emissions[4] by 60 – 80% by 2050 (EU 2007). These cuts are meant to "ensure that global average temperature increases do not exceed pre-industrial levels by more than 2°C" but nowhere is carrying capacity mentioned (EU 2007). The IPCC has influenced the Architecture 2030 initiative in the United States, which drives all new and remodeled buildings toward zero operating carbon emissions by 2030. This initiative, which has garnered support from the American Institute of Architects (AIA) and the United States Green Building Council (USGBC), likewise fails to identify carrying capacity as the driver behind the logic of its work.[5] It is worthwhile to attempt to understand this lack of discussion of carrying capacity.

There are at least three forms of resistance to an explicit reference to carrying capacity. One is the perception that a free society and carrying capacity are mutually exclusive. Another arises out of the sheer difficulty to determine an accepted value for carrying capacity. A third resistance is from the techno-optimists who believe human ingenuity can overcome physical limits to societal growth. Each of these will be discussed in turn.

We live in a technological society where the freedom to know everything and to expand in new directions is highly valued. This has been true in western society since at least Rousseau's *The Social Contract* and the Industrial Revolution. In this historical context, as society moves in the direction of sustainable development, it is understandable that targets for reduction would be

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[4] Henceforth, "carbon emissions" will be used to indicate the gaseous emissions that cause the greenhouse effect. These gaseous emissions are also referred to as "carbon equivalent," "greenhouse gas emissions," and "global warming potential."
[5] www.architecture2030.org

favored over recognition of carrying capacity. Target emissions cuts imply a sense of freedom; that is, we, as a society, are choosing to treat the environment better. We are just as free to choose targets for reduction as we are to let carbon emissions grow indefinitely. On the other hand, physical limits are restrictions presented to us by nature and are not freely chosen. To further expound the point: If the so-called Green Revolution borrowed the spirit of the French Revolution but modified the motto: "~~*Liberté*~~ *Capacité, Egalité, Fraternité,*" very few would support it for its very lack of liberty. In addition, the motto "Liberty, Equality, Fraternity, and Capacity," as it were, would be unbelievable from this perspective because liberty and capacity are seemingly exclusive to most people in modern day society.

Another source of resistance has to do with the difficulty in the quantification of the carrying capacity concept. Carrying capacity and its conceptual cousin, physical limits, are affected by complex variables including abundance of the resource and the rate of depletion. The so-called "science of sustainability" is nascent and lacks a cohesive framework enjoyed by the older scientific disciplines. The aforementioned ecological footprint assessment is the only existing method to quantify carrying capacity[6] and thus far provides the only way to discuss it quantitatively.[7]

A final possible explanation to the lack of explicit presence of carrying capacity comes from the techno-optimists. It is claimed that human ingenuity will allow us to extend physical limits such that they no longer exist. For example, NASA considers it a possibility to learn to live off of lunar soil and to mine the moon for Helium-3, which can be used for nuclear power (Carey 2005). The National Academy of Engineers states, "the growth in emissions of carbon dioxide, implicated as a prime contributor to global warming, is a problem that can no longer be swept under the rug. But

[6] Incidentally, the science is having a remarkable amount of societal impact. For instance, the Global Footprint Network (GFN), the original ecological footprint assessor, is currently working toward institutionalizing the method in national governments. According to GFN, "Switzerland has completed its national review, and national reviews are underway in Japan, Belgium, the United Arab Emirates, Ecuador and France" (www.footprintnetwork.com).
[7] Agenda 21 speaks of carrying capacity qualitatively.

perhaps it can be buried deep underground or beneath the ocean."[8] These engineering "fixes" would theoretically allow us to transcend our state of limits – by providing more land, more energy, and a reduced greenhouse effect. Simply put, techno-optimists do not want to believe in carrying capacity.

2.3 Empowerment through affirmation of physical limits

The strange phenomenon that members of our society most interested in sustainable development fail to acknowledge physical limits prompts further discussion of physical limits. In no way an exhaustive account, this section provides further explanation of the aforementioned techno-optimist resistance and develops the following key conclusion: not only does carrying capacity provide a point of reference as suggested in Agenda 21, but also a more empowering way to view the world. Consider the following from philosopher Simone de Beauvoir:

> [Man] extends his control of the world by instruments which enable him to devour distances and to multiply the output of his effort in time; but he is always only one. However, instead of accepting his limits, he tries to do away with them. He aspires to act upon everything and by knowing everything. Throughout the eighteenth and nineteenth centuries there developed the dream of a universal science which, manifesting the solidarity of the parts of the whole also admitted a universal power [that is technology]; it was a dream "dreamed by reason," as Valery puts it, but which was none the less hollow, like all dreams…
>
> Just as the infinity spread out before my gaze contracts above my head into a blue ceiling, so my transcendence heaps up in the distance the opaque thickness of the future; but between sky and earth there is a perceptional field with its forms and colors; and it is in the interval which separates me today from an unforeseeable future that there are meanings and ends

[8] http://www.engineeringchallenges.org/cms/8996/9077.aspx [Accessed November 2008]

> toward which to direct my acts. As soon as one introduces the presence of the finite individual into the world, a presence without which there is no world*, finite forms stand out through time and space.*
>
> *The Ethics of Ambiguity* (1948)
>
> (emphasis added)

With the emergence of modern science and technology came a seeming rejection of finite forms and the physical limits that come with them. Extraordinary advances in human productivity during the industrial age led to dreams of boundless human action. Nanotechnology, genetic engineering, space exploration, and atomic physics continue to tantalize us with limitless transformation of our world and ourselves. De Beauvoir poetically describes this "hollow" dream.

While errors and dangers of the technological dream have been thrown into relief in philosophical ways, *The Limits to Growth* (1972) cast the first scientific light. By contradicting the common industrial age belief that nature is an infinite pollution sink with a limitless supply of materials and energy, this work provided the first quantitative method to alert us to the unintended consequences of industrial development (Meadows et al 1992). Its computer model quantified limits to natural resources and pollution sinks in order to juxtapose them with societal consumption and waste generation. This model predicted societal collapse within decades due to exceeding these limits. *The Limits to Growth* helped to create a major paradox – if not *the* paradox – in the age of sustainability, one that accounts for the seeming avoidance of carrying capacity: modern science argues for the existence of physical limits yet modern technology at the same time encourages their transcendence.[9]

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[9] Transcending physical limits can be understood as believing they are not really limiting or, alternatively, forgetting that they exist. This discussion is about the former. For an exposition of the notion that modern technology encourages forgetting, see Martin Heidegger's seminal essay "The Question Concerning Technology" (1954).

The Limits to Growth was criticized for neglecting the ability of humans to technologically reshape their environment (Meadows et al 1992 p. xiii). It is true that we have powerful abilities. Bioengineering allows for the genetic redesign of organisms to fulfill various needs such as nutrition and resistance to disease and pests, it also allows for better integration with our technological milieu: firmer tomatoes to resist crushing, an extended ripening period for bananas, etc. One woman has reshaped her experience with death itself by cloning her deceased cat (Fimrite 2004). Human mental and physical abilities are in general being amplified by technology, especially by nanotechnology, which is creating no less than a societal fervor for its potential power (Mitchell 2004). A new frontier of manipulation can be seen in a geoengineering strategy to prevent global warming. This idea is not to decrease anthropogenic disruption of the ecosystem, as is achieved through energy efficiency and renewable energy, but the opposite: the surface albedo of the earth is to be increased by covering up to four million square miles of desert with a white plastic sheet; this strategy was presented to the US Department of Energy in 2004 (Gaskil 2004).

These few examples and others like them tell us that we will always be able to reshape our environment and, when presented with physical limits, there is always a way to push them back. Thus, knowledge becomes based on precedence in an unreasonable way, such that even for the scientist or engineer, technology becomes a nebulous concept – a "dream" – that is no longer grounded within the physical limits of scientific reality. Perhaps the most famous (and controversial) representation of this worldview was in the article "The Death of Environmentalism" which advocated political and financial "investment" and denigrated recognition of limits (Shellenberger and Nordhaus 2004, Shellenberger and Nordhaus 2007).

An alternative reaction to *The Limits to Growth* was not to push against but to back away from physical limits. According to this view, human needs can be met – moreover, humans can be prosperous – with less energy and material flow. In 1977, Amory Lovins wrote "many people…still cling to the bizarre notion that using less energy – or, more often, failing to use much more energy – nevertheless means somehow a loss of prosperity" (p. 7). Lovins' thought, which benefited from the work of economist Herman Daly, inspired current tools and initiatives that attempt to shift technology toward "new and less resource demanding and more ecologically and socially sound ways of satisfying the same human need" (Robért et al 2002 p. 200). A key component of these approaches is de-materialization. The decision to de-materialize is due precisely to the understanding that the ecosphere presents us with physical limitations. For The Natural Step Framework, Factor 10, Ecological Footprinting, Sustainable Technological Development, UNEP/Cleaner Production, Zero Emission, and Natural Capitalism:

> the overarching system that we are focusing on, i.e. the societies and the surrounding ecosystems…also referred to as the *ecosphere*, occupies the full space above the lithosphere (earth's crust) to the outer limits of the atmosphere. Hierarchically different levels of principles for planning within this system must be based on an understanding of the constitutional principles of the functioning of this system (e.g. thermodynamics; the biogeochemical cycles; the ecological interdependencies of species; the societal exchange with, and dependency on, the ecosphere).
>
> Robért et al 2002 p. 198

These tools and initiatives operate with the physical science understanding that materials and energy are continuously flowing and interacting within the ecosphere. In this way, there are unmovable limits to societal growth.

De Beauvoir points out that the forms along our view to the horizon give us a sense of orientation and are the "meanings and ends toward which to direct [our] acts." In other words, to the extant that we better identify limits and demarcations, we are better able to know the meaning of our designs. This reliance on one's own perceptions rather than the mysterious power of technology to push back limits ironically does not limit the individual but empowers him or her with better knowledge and more effective ideas. The understanding that limits exist no doubt inspired the authors of *Natural Capitalism* to write:

> There are armfuls of books describing how technology is revolutionizing our lives. While that is undeniably so, at least for a minority of the world's population, our purpose is almost the opposite. We are trying to describe how our lives and life itself will revolutionize all technologies.
>
> Paul Hawken, Amory Lovins, and L. Hunter Lovins
>
> *Natural Capitalism* (1999)

2.4 Conclusion

A complete historical and philosophical account of the concept of physical limits to societal growth would have occupied too large a space for this thesis; rather, this chapter was meant to give a broad overview with some elements of detail. Ever since being defined in *The Limits to Growth,* the concept of physical limits has been denigrated by popular society. Even ecological footprint assessment, which has introduced the popular "carbon footprint" terminology, has not been able to introduce its biological carrying capacity concept to our vernacular. There is a clear resistance to the idea that we are limited by nature. We would much rather freely choose to reduce pollution rather than acknowledge some limit imposed on us.

This chapter showed that the negative reputation of physical limits in popular society is unwarranted. There is a certain empowering effect with recognizing our limits in the world. When we begin to believe that we live in a world of limits, our concern shifts from what technology can do, to what we can do. This sense of empowerment can be seen in the major sustainability initiatives. The emphasis for these initiatives is de-materialization and radical energy efficiency such that we are able to back away from the limits without much sacrifice in the conveniences of our modern age.

Carrying capacity is a concept that can benefit building environmental assessment methods. We can deduce from this chapter that the concept can provide for building stakeholders a sense of orientation and empowerment with regard to achieving sustainability.

Chapter 3: Building environmental assessment methods

Building environmental assessment methods influence both the design process as well as the building product. The introduction of the Building Research Establishment Environmental Assessment Method (BREEAM) in 1990 marked the beginning of building environmental assessment. Since then several different assessment methods have emerged around the world. A major initiative to develop a single tool for international use, known as the Green Building Challenge, has given way to academic discourse that has clarified the intent and content of these methods (Cole and Larsson 1999, Cole 2005). It can be safely said that building environmental assessment has become its own discipline, with topical papers typically published in *Building Research & Information*, *Building and Environment*, and *Solar Energy*.

This chapter will provide a narrative of from where building assessment methods have come and where they are going. The first section will provide an overview of the methods in terms of their societal purpose and function (section 3.1). It will then describe how assessments influence the design process and the building product (section 3.2), including a description and discussion of how two systems have incorporated Life Cycle Assessment. The chapter then turns toward two major criticisms of the methodological development of systems: one, assessment content remains too subjective and, two, almost no attention is paid to developing the impact methods have on the design process. Responses to these two criticisms are critically reviewed in section 3.3.

3.1 Societal purpose and function

Environmental assessment methods "were initially conceived, and still largely function, as voluntary, market place mechanisms by which owners striving for improved performance would have a credible and objective basis for communicating their efforts" (Cole 2005, p. 458). Ultimately, it is often stated, these methods were meant to transform the market place to expect and demand greater building environmental performance (Cole 2005).

The methods create a sense of competition between building stakeholders by comparing the assessed building with standard practice. It is assumed that with the leadership of one group in environmental responsibility, others will follow to achieve the same recognition (Cole 1999). To a certain extent this assumption is proving itself true as the number of certified buildings grows internationally.

3.1.1 Expected development

The mental landscapes of influential members of our society are shifting and vacuous spaces are opening for building environmental assessment. Books like *Natural Capitalism* and the field of ecological economics conjoin how we understand (ecology) and how we behave (economy) in our world.[10] In general, ecology and economics are two disciplines that are being driven together.

Investors are beginning to see an inverse correlation between ecological sustainability and risk (i.e., economic non-sustainability). Developments such as corporate social responsibility (CSR) and socially responsible investment (SRI); ethical and social reporting guidelines as published by the Global Reporting Initiative and the Institute of Social AccountAbility; and the Dow Jones Sustainability Index and FTSE4 Good Index Series have been identified as ways for corporations and other institutions to demonstrate to investors they contribute to sustainability and are therefore less risky. Building environmental assessment methods can be used as documentation for that process. (Lutzkendorf and Lorenz 2006)

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[10] It is revealing to etymologically dissect ecology and economy. For both words, the root "eco" is *oikos*, Greek for home. Ecology refers to how our home is put together, or how we talk about it (*logos*). Economy refers to the laws or manners (*nomos*) that we set up in our home.

Property professionals are increasingly interested in drawing correlations between a building's market value and its environmental performance. For some these correlations are already becoming solidified, as European lenders have already adopted a new property and market rating system that includes a section on sustainability. (Lutzkendorf and Lorenz 2006)

Assessment methods increasingly are fulfilling a role in government intervention with the economy. More municipalities in the US are setting mandatory building performance targets for government buildings.[11] The State of Colorado now offers incentives to school districts to agree to Leadership in Energy and Environmental Design (LEED) certification.[12] In addition, the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan is promoted by a nation-wide government action plan (Endo 2008).

3.2 Assessment process and content

Building environmental assessment methods typically do two things: 1) facilitate an integrated design process and 2) assess the expected environmental performance of the produced building. Not all methods emphasize the former, but all perform the latter. The LEED system is perhaps the most well known facilitator of an integrated design process. Early in the design it is typically encouraged that a wide selection of project stakeholders decide on a communal goal of an overall rating and, to a certain extant, which design strategies are to be employed. This integrated design process allows for a communication between architects, engineers, and other stakeholders that normally does not take place. As will be discussed in section 3.3, the development of this side to assessment methods has been neglected in favor of developing the assessment of the produced building.

[11] USGBC News and Events (accessed online, October 2008) http://www.usgbccolorado.com/newsevents/documents/USGBC_CO_SepOct07.pdf

[12] Colorado Governor's Energy Office (accessed online, October 2008) http://www.colorado.gov/energy/

For assessing the produced building, or what is here called the assessment content, most methods have a list of criteria for which points are awarded. The points are tallied and the building achieves a rating such as certified, gold, or platinum; or in the case of CASBEE, a level of "building environmental efficiency." These criteria typically fall under resource use, ecological loading, and indoor health and comfort (Cole 2005). Energy assessment is typically made in regard to expected building operational energy consumption and the embodied energy; however, for the great majority of methods, only operational energy is directly quantified.[13]

For assessment of operational energy consumption, credit is given in two ways. One is on a comprehensive basis, that is, energy consumed as evidenced by a building energy model or measured performance. The other is on a component basis, that is, using a particular strategy to mitigate energy use, such as ongoing commissioning, access to mass transit, and daylight autonomy. Regarding the former, in most methods the expected energy use of the assessed building is compared to standard practice. One method, the Living Building Challenge from Cascadia Green Building Council, requires the building to be net zero site energy.[14] There is no existing method that compares energy consumption to carrying capacity.

The same component versus comprehensive distinction can be made for the assessment of embodied energy. Most methods typically account for components such as recycled content, delivery distance, and building reuse; however, it would be more accurate to measure the energy consumed. This can be done using life cycle assessment (LCA). There are at least twenty-one LCA tools for buildings around the world, including sixteen in Europe, that can directly quantify the embodied energy of materials and other aspects of buildings. Given the apparent availability of data, it is surprising that only two assessment methods – Green Globes and CASBEE – include an LCA. This can be explained by the fact that LCAs have typically been time intensive processes requiring

[13] International Energy Agency's Annex 31, Directory of tools http://www.iisbe.org/annex31/Main/dir_tools.htm
[14] Cascadia Green Building Council http://www.cascadiagbc.org/lbc

Table 3-5. Comparison of the boundary of assessment of CASBEE and Green Globes LCA.

Comparing the Life Cycle Assessment Boundary of Analysis of Green Globes and CASBEE								
Aspects of the analysis for each part of the building	Structure	Walls, ceiling, roof, windows	HVAC equipment	Plumbing	Other electrical	Lighting Fixtures	Other finish materials	Furnishings
Raw materials extraction	Green Globes, CASBEE	Green Globes, CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE
Manufacturing	Green Globes, CASBEE	Green Globes, CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE
Transportation	Green Globes, CASBEE	Green Globes, CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE
On-site assembly	Green Globes, CASBEE	Green Globes, CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE
Maintenance	NA	Green Globes, CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE
End of life deconstruction	Green Globes, CASBEE	Green Globes, CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE
Design services	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE	CASBEE

Users determine the LCA of their building and a reference building regarding both operational and embodied carbon emissions. For the operational carbon emissions, users choose the space type and area of the building in order to determine a reference value. They then enter the expected energy use for their building based on a percent decrease from average or an energy model. For the embodied carbon emissions, users choose from a list of nine commercial spaces, choose one of three types of construction (steel [S], reinforced concrete [RS], and steel reinforced concrete [SRC]), and enter the gross area. Users can decrease the embodied carbon emissions for their building only if it has some element of building structural reuse and/or use of blast furnace slag cement. The amount of carbon emissions savings is calculated from Table 3-2 below. Users must interpolate in order to find the embodied carbon emissions of their building. For instance, the embodied carbon emissions of a 1000 m^2 steel office building with 25% of the structure reused would be calculated as follows:

$$CO2 = S + (1 - R)(AVE - S)A$$

Where

CO2 = total embodied carbon emissions of building project (kg CO_2)

S = embodied carbon emissions when 100% of structure is reused (kg CO_2/m^2)

R = percent of structure reused (%)

AVE = average embodied carbon emissions for space type (kg CO_2/m^2)

A = area of building (m^2)

$$= (6.54 + (1 - 0.25)(13.61 - 6.54))1000$$

Building type			S	RC	SRC
Offices			13.61	13.85	13.92
	LR2/2.2 Existing building structural skeletons	100%	6.54	6.67	6.57
	LR2/2.3 Recycled materials (blast furnace cement)	100%	12.71	12.60	12.81
Schools			10.24	12.66	14.51
	LR2/2.2 Existing building structural skeletons	100%	5.45	5.48	5.48
	LR2/2.3 Recycled materials (blast furnace cement)	100%	9.68	11.28	12.98
Retailers			16.13	24.24	16.74
	LR2/2.2 Existing building structural skeletons	100%	8.57	8.75	8.61
	LR2/2.3 Recycled materials (blast furnace cement)	100%	15.04	21.36	15.76
Restaurants			16.13	24.24	16.74
	LR2/2.2 Existing building structural skeletons	100%	8.57	8.75	8.61
	LR2/2.3 Recycled materials (blast furnace cement)	100%	15.04	21.36	15.76
Halls			10.96	13.47	13.59
	LR2/2.2 Existing building structural skeletons	100%	5.61	5.72	5.64
	LR2/2.3 Recycled materials (blast furnace cement)	100%	10.41	12.03	12.22
Factories			18.18	22.71	23.15
	LR2/2.2 Existing building structural skeletons	100%	9.73	9.74	9.76
	LR2/2.3 Recycled materials (blast furnace cement)	100%	17.06	20.28	21.04
Hospitals			10.39	13.24	14.18
	LR2/2.2 Existing building structural skeletons	100%	6.56	6.69	6.59
	LR2/2.3 Recycled materials (blast furnace cement)	100%	9.88	12.00	12.88
Hotels			10.92	13.97	13.89
	LR2/2.2 Existing building structural skeletons	100%	5.81	5.92	5.83
	LR2/2.3 Recycled materials (blast furnace cement)	100%	10.23	12.35	12.58

Table 3-6. Embodied carbon emissions of reference and evaluated building construction is linearly interpolated from this table (units of kg CO_2/m^2) in the CASBEE technical manual.

After reductions in both operational and embodied carbon emissions are accounted for, users reference Table 3-3 to determine their performance, which contributes to the overall CASBEE rating.

LR3: Off-site environment		
1. Consideration of Global Warming		
Level 1-5	Level 1	Life cycle CO_2 emission rate is 125% or more of the reference value.
	Level 3	Life cycle CO_2 emission rate is 100% of the reference value.
	Level 5	Life cycle CO_2 emission rate is 75% or less of the reference value.

Table 3-7. The highest credit is given to a 25 percent reduction in life cycle CO_2 (embodied and operational) emissions.

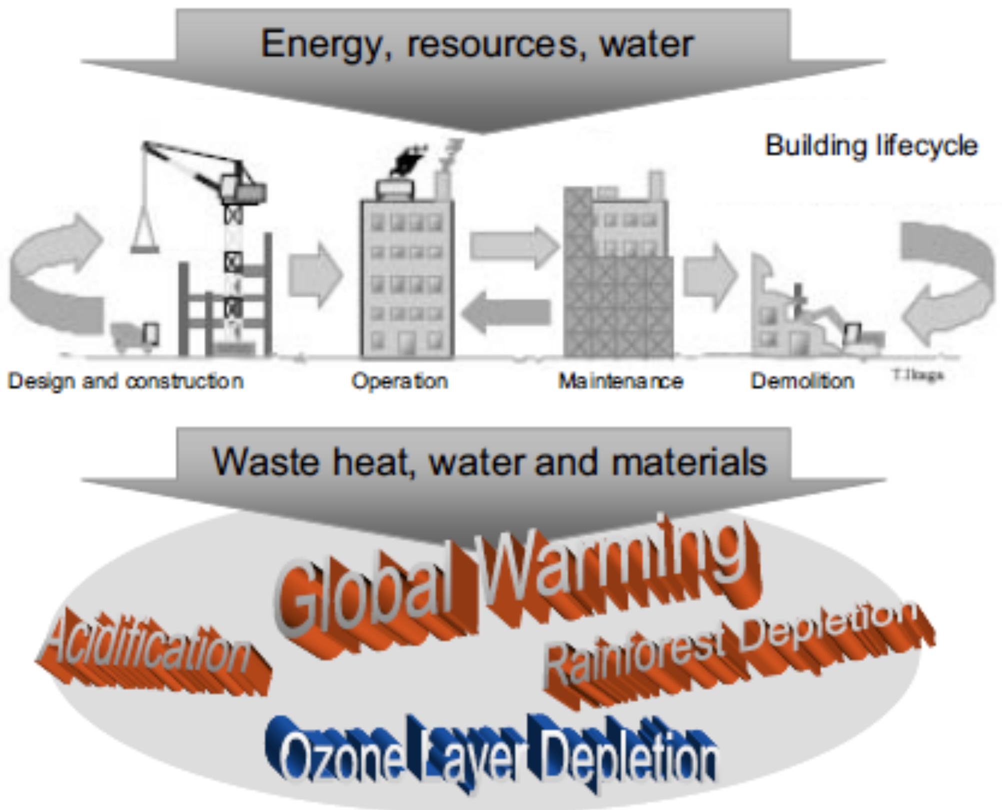

Table 3-8. CASBEE illustration of impact on global environment from buildings.

3.2.4 Discussion and conclusion

The LCA methods of Green Globes and CASBEE are good in different ways. As stated before, an ideal LCA would

- Measure the environmental impacts of all aspects of a building project; and
- Reveal to designers and other stakeholders where they can have direct influence on the mitigation of that impact.

CASBEE does a better job with the former, while Green Globes is better equipped for the latter. From the boundary of assessment comparison in Table 3-1, it is clear that there are several aspects of a building project for which Green Globes does not account. Nonetheless, using the CASBEE approach, the only direct impact designers can have on the embodied energy of their building is regarding structural reuse or the use of blast furnace slag cement. Given the highly aggregate nature of the CASBEE method it is perhaps inherently difficult to reveal many points of leverage for the designer. So, in general, there is really no clear answer as to which method is best.

However, one method may be better than the other at different stages in the building design. For instance, during the pre-design stage it would be beneficial to have a quick estimate of the embodied carbon emissions of materials simply based on space type and square footage, as provided by the EIO-LCA-based data in CASBEE. This can be used for illustration of what is entirely at stake in terms of environmental effect, and could influence early decision-making on building re-use (if applicable) and use of lower embodied energy cement. As the design progresses and decisions are being made about building assembly types, then the assembly-specific data in the process-based LCA Athena EcoCalculator used by Green Globes can have influence. As described above, designers can evaluate different assembly types based on environmental effect. Accordingly, it seems the method in CASBEE is better suited for the pre-design stage while the Green Globes method is better for the later stages.

3.3 Green is the answer! (But what was the question?)[1]

Now that building environmental assessments are gaining more influence in the market it may be the right answer to get a building certified, but what is the question that prompted the answer? It is easy for these systems to create their own necessity. The ultimate intent of the systems can become transformation of the market rather than the built environment. In order to avoid this, these assessments need to continually develop rigor and accountability. A major criticism that dates back to the nascent period of building environmental assessment has been a lack of objectivity, especially in the energy assessment. Effort has been made to benchmark energy assessment values across different systems (Lee and Burnett 2008), but the assessment is still made relative to typical buildings rather than a more absolute measure. Another major criticism is made on the way methods develop. Developers typically focus on the assessment content, rather than the design process. These two major criticisms should inform future method development.

3.3.1 Discussion of absolute measures for buildings

There has been made a distinction between "green" and "sustainable" assessments, the latter being ideally based on absolute measures (Cole 1999). A measure produced by an established science is considered in Cole (1999) and in this thesis an absolute measure.[2] There have been purported at least two absolute measures for buildings and there is one additional possibility: (1) using the Ecological Footprint method, (2) using net zero energy, and (3) using data from the Intergovernmental Panel on Climate Change (IPCC).

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[1] This section title is modified from the introductory chapter title of *Soft Energy Paths* (1977) by Amory Lovins, "Technology is the Answer! (But What Was the Question?)"

[2] There is strong objection to the statement that science can produce absolute truth, in at least philosophy as well as science, technology, and society (STS) studies. For instance, Heidegger (1982, pp 155–182) describes how science creates truth only in the sphere of science. The *No-Nonsense Guide to Science* (Ravetz 2007) describes how science tends to impose its truth structure on the rest of society.

3.3.1.1 Carrying capacity approach: Ecological footprint method

In 2004, Olgyay and Herdt presented an assessment method to determine the ecosystem services attributable to a building project and the commensurate stress on those services. Using the global average ecosystem productivity in units of gigajoules per hectare-year, as determined by Wackernagel and Rees (1996), a carrying capacity was established based on the size of the building project site. This carrying capacity was then compared to the embodied and operational energy consumption of the building. If the building uses more energy than is currently being produced on site, then, according to the method, it is not sustainable. In this way, an absolute measure was created for building environmental assessment.

Another unique aspect of the Olgyay and Herdt (2004) method was an assessment with regard to time. It was identified that net zero energy buildings and energy producing buildings all would fit well within the carrying capacity of the site. Yet, when the embodied energy is measured, the environmental effect of the building extends well beyond what is produced on site. So even a net zero energy building is truly not sustainable due to the impact of the embodied energy. The embodied energy, therefore, can be thought of as an "ecological debt" that only a "regenerative" building can earn back through energy produced on site or increased land productivity (Olgyay and Herdt 2004).

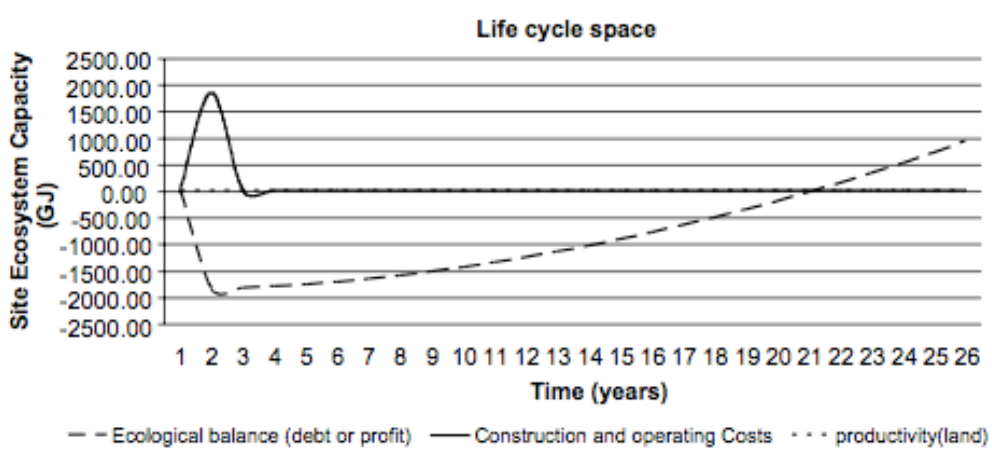

Table 3-9. The concept of earning back an ecological debt incurred with building construction.

While providing an innovative framework for future building assessment – and the primary stimulus for this thesis – the method of Olgyay and Herdt (2004) can be criticized in at least two respects. The first has to do with its method of assessing carrying capacity.

There are at least two major ways to assess carrying capacity of a building project. One is site specific, in that the aim is to identify exactly the level of ecosystem services provided on site. The other is more global: to assess exactly the fair share of the building project. "Fair share" estimates can be made in a number of ways, including an equitable anthropocentric distribution or a distribution based on the size of site or the building square footage. EFA distributes carrying capacity based on the Agenda 21 principles of human equality, i.e., an equitable anthropocentric distribution.[3] Given that Olgyay and Herdt use the global productivity average (100 GJ/ha), the same base unit of EFA, it seems they intend to determine carrying capacity for building projects also using a global distribution, as opposed to one that is site specific. Except their distribution is not made anthropocentrically, rather, it is based on size of site.

Since the intent of Olgyay and Herdt seems to be an equitable, global distribution (rather than site-specific), some may argue that the Olgyay and Herdt distribution wrongly ignores the question of human equality. For instance, people who are building on a larger site are able to use more ecosystem services. Yet, since the intention of the Olgyay and Herdt method is to assess buildings and not people, it does not seem necessary that human equality be taken into account. The question of sustainability is not about people who are building, but the building project itself.[4]

However, there is a major source of uncertainty in defining carrying capacity for buildings using a common denominator for all ecosystem services, i.e., the global productivity average of 100

[3] The Footprint Network has calculated that the total productive area per person is 2.1 global hectares (Living Planet Report 2008).

[4] It is important to note that while the assessment is concerning a building project, the people behind the project (i.e., stakeholders) are the ones who shape the project and are therefore responsible for its environmental impact.

GJ/ha. This figure was calculated by EFA based on all the ecosystem services that are available for humans to consume (see Figure 3-7 below for a breakdown of the aspects to an ecological footprint). By using this figure, Olgyay and Herdt, in effect, assigned carrying capacity for food and fiber as well as non-fiber building materials, energy, settlement land, timber, and seafood. Since buildings cannot consume all types of services humans can, the services they do not consume artificially inflate the total allocation. For buildings, then, it would be most accurate to account for availability and consumption for each ecosystem service separately. For instance, the food and fiber footprint should be compared to a food and fiber allocation, the energy for the carbon, timber for forest land, etc.

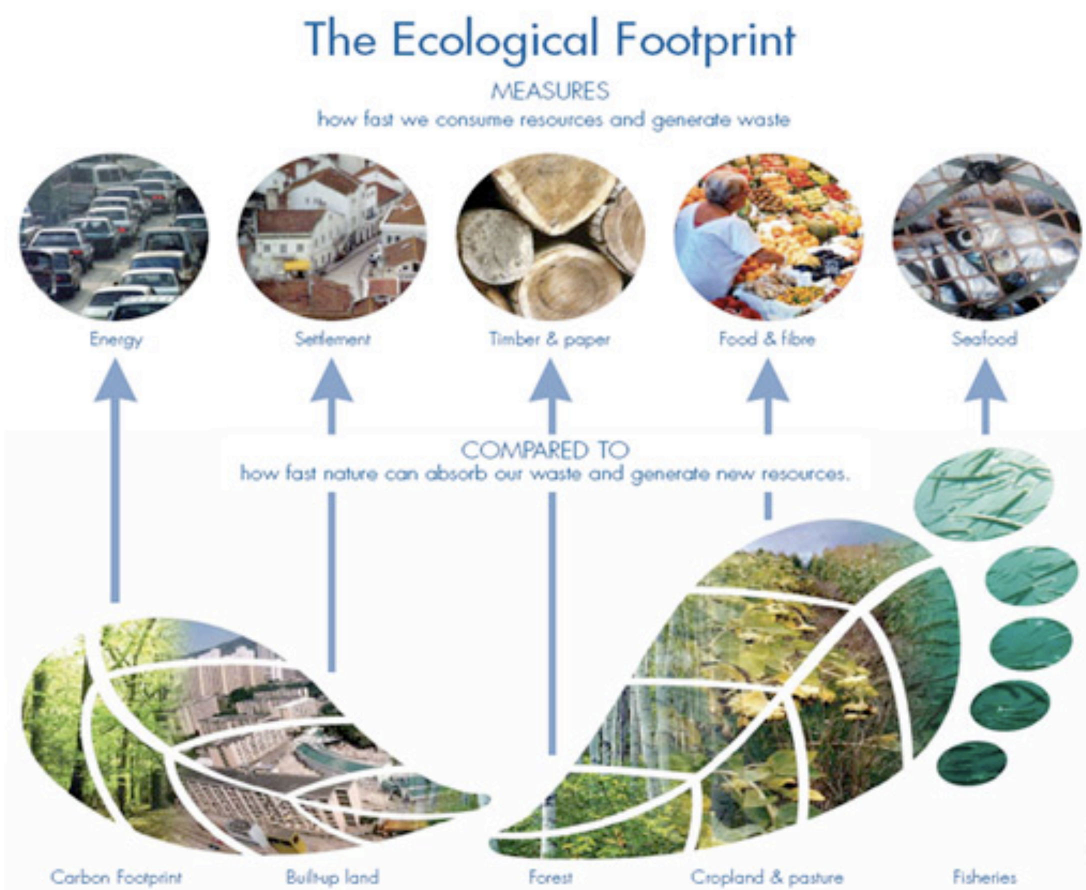

Table 3-10. EFA divides societal consumption into five different categories. (www.footprintnetwork.org)

The second criticism is concerning the calculation of the ecological debt and payback period. The ecological footprint framework was not meant to predict quantitative ecological debt, only to provide a snapshot of the state of our society and the general direction and magnitude we need to move (Ewing et al 2008). Given that energy cannot be created nor destroyed, if the rate at which energy is converted into useful energy (i.e., net ecosystem productivity) is smaller than the rate at which we consume, we are tapping into the stored productivity on the planet. This can be seen in deforestation, depletion of fisheries, and burning of fossil fuels. If we were to account for this time spent in "overshoot," or exceeding the rate of global productivity, than we would need to take the integral of the consumption and carrying capacity curves. So in order to generate ecological debt curve as shown in Olgyay and Herdt (2004), the total capacity of our planet would need to be determined not as a rate but as a sum. This important detail did not seem to be accounted for in the paper. In addition, EFA would only be able to estimate the debt incurred using a calculative method that sums the difference in consumption and capacity rates.

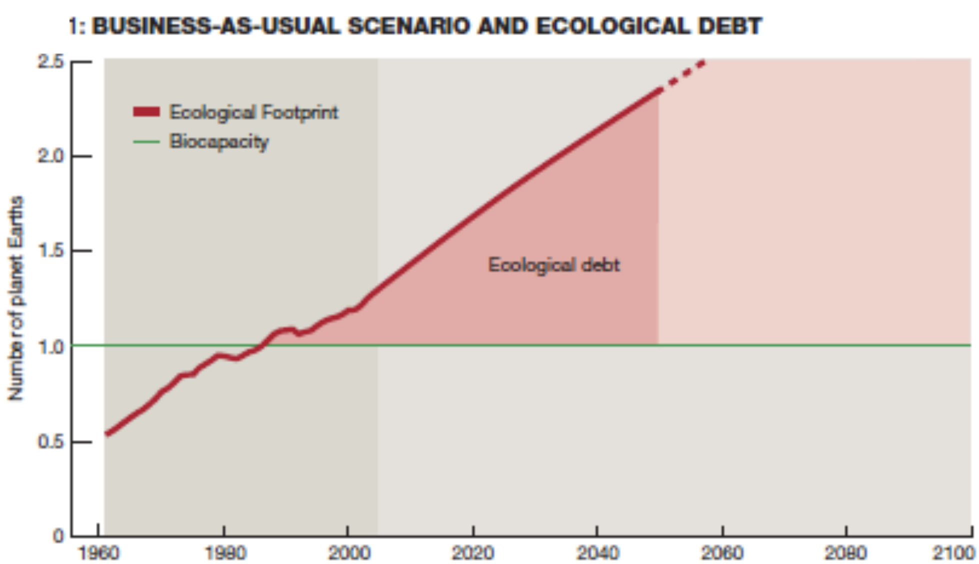

Table 3-11. Ecological debt. As illustrated in the 2008 Living Planet Report from the World Wildlife Fund, in collaboration with the Global Footprint Network, an ecological debt could theoretically be calculated. However, EFA methodology does not attempt to calculate this debt or estimate how it could be repaid.

3.3.1.2 Target for reduction approach: Net Zero Energy Buildings

Net Zero Energy Buildings, or NZEBs, are perhaps the most well known absolute measure of building sustainability. The aforementioned Architecture 2030 Challenge is an initiative to design all new and renovated buildings to zero site energy by 2030. ASHRAE has recently begun an initiative to "provide to its members by 2020 the tools necessary to design, construct, and operate NZEBs" (ASHRAE 2008 p. 3). In addition, the Cascadia Green Building Council's Living Building Challenge rating system requires buildings to be net zero site energy.

However, little effort has been made to identify the significance of using net zero energy as a measure of building performance. More effort has been made on defining the measure itself. There are several ways to define a NZEB, such as site energy, source energy, energy cost, and energy emissions (ASHRAE 2008). There is general agreement between ASHRAE, the AIA, USGBC, and IESNA on defining it based on site energy. The justification for this decision was more based on data availability than anything else, i.e., the "measured information" and "weighing factors and algorithms" required by the other definitions did not seem readily available (ASHRAE 2008 p. 4). While this is an important practical consideration, it still remains possible to define the ideal significance of such a goal. The key questions that need to be asked are:

- With regard to carbon emissions, does a sustainable society require net zero energy buildings?
- What is the difference in terms of carbon emissions between the alternative definitions of NZEB?

Heretofore, a positive answer to the first question has been assumed and the second question has not yet been the subject of a study. Studies from Architecture 2030 are more about the effect buildings now have on climate change than the effect of all buildings shifting to net zero site energy. Given that the justification for the initiative is climate change, it would be most appropriate to base the measure on carbon emissions rather than on site energy consumption. Neither Architecture 2030 nor any other body that supports NZEB has looked in detail at the effect of the realization of their common goal. Given that the general magnitude and direction of the vector is likely true – i.e., building energy consumption needs to decrease dramatically – it is no small surprise that not much time has been spent on the details of these questions. Like the first generation of building environmental assessment methods, the intent of the NZEB initiative was to garner a broad-based support for transformative building design.

However, now that there is significant support of NZEBs and several have been built, it is appropriate to begin fine tuning the goal to be in accordance with an overall picture of sustainability. Until then, the NZEB goal is more an exercise in mathematics (energy in = energy out) than a significant goal founded on an established science.

3.3.1.3 Target for reduction approach: Intergovernmental Panel on Climate Change

Another way to define an absolute measure for a building is based on reports from the IPCC. This United Nations panel has used various scientific data sources regarding the carbon cycle and the greenhouse effect to estimate that the developed nations in the world must cut carbon emissions by 80% by 2050 in order to avoid catastrophic effects of climate change (IPCC 2007). The EU has adopted this goal as well as President-elect Barack Obama.[5] The translation of this goal to one for building projects can be relatively straightforward. A tool such as Energy Star's Target Finder can be used to estimate the "average" building. The associated carbon emissions emissions can be estimated with that tool, but the emissions coefficients do not currently include transmission and distribution losses, even though these coefficients are available (though hard to find) on the

[5] Office of the President-Elect. http://www.change.gov/agenda/energy_and_environment_agenda/

Energy Information Administration's Voluntary Emissions Reporting website.[6] Once a baseline emission is determined, using Target Finder's or another set of emissions coefficients, it can be cut by 80%. In order to account for embodied energy, the same cut would need to be applied to an estimate of "average" as well. Since it would be nearly impossible to cut the embodied emissions by 80%, this goal could be met with carbon offsets, as it is presented in the Cascadia Green Building Council's Living Building Challenge (except 100% of the embodied emissions must be offset in that rating system). Alternatively, the concept of ecological debt and payback could be employed. The debt incurred from construction could be paid back a little each year throughout the life of the building through carbon offsets or on-site production of renewable energy distributed to the grid.

One major drawback about the approach based on IPCC data is its reliance on an "average" value determined by a tool such as Target Finder or an energy model. Determining a "base case" building, especially in the early design stage when there is no specific energy model, can be a highly contested and subjective process. This is important to mention because neither the carrying capacity nor NZEB approach requires these base case estimates.[7]

A positive attribute of the IPCC approach is that it can be considered a direct measure of the effect of buildings on climate change. In this sense, it is more of a comprehensive or global analysis than the other two. The global analysis does a better job of linking goals for individual building projects to the goals that seem to be forming for governments and society as a whole.

3.3.2 Improving the design process

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[6] The author needed to personally telephone the EIA to discover where these estimates are located. Needless to say, carbon accounting in the US government requires improvement. http://www.eia.doe.gov/oiaf/1605/techassist.html

[7] Energy modeling can therefore be used solely to inform the design team on different design strategies, rather than to determine the official base case.

In addition to a lack of an absolute measure, another major criticism has been made against innovators who are focused on bettering the assessment content rather than the design process. A focus on the assessment content drives further development of the scoring process or presentation of results (Cole 2005). Cole (2005) argues once again (as he did in 1999) that we need to evaluate the intention of these methods. They continue to be "market transformation tools" but there is a need for them to "enhance dialogue across a range of stakeholders" (Cole 2005, p 455). The design process is the time when decisions are made about what becomes the end product. A great variety of personalities and people with far different incentives can be involved. So the assessment method could potentially reach a state of development where it can fulfill the need for a guide through this process.

There are a number of ways an assessment method can guide the design process. Shortly after the introduction of LEED, some consultants began organizing LEED charrettes to facilitate integrated design (Olgyay 2008). These charrettes were typically one or two days of goal setting and intensive strategizing that brought together all members of the design team. While sometimes very effective, charrettes are not currently required by LEED nor does a charrette earn LEED credits. In general, Kaatz et al (2006) argues that assessment methods can better inform the design team through any strategy that brings about integration; transparency and accessibility; and collaborative learning.

One negative way that LEED and other assessment methods affect the design process is when stakeholders engage in "points chasing." This occurs when the individual points rather than the building as a whole drive the design. Points chasing can lead to a less integrated design process.

A general research topic can be to identify the positive, negative and neutral influence of current assessment methods on the design process. There is currently at least some activity in the development of design workshops, such as "value based design charrettes."[8] As of right now, there is little effort being made to link this research to building assessment methods.

3.4 Conclusion

The environmental assessment of buildings has come to define our progress toward sustainability. As they become more infused to societal and economic processes, they take on greater responsibility to not only transform the market but to transform the built environment. Now, more than ever, it is necessary to know how assessment methodology should improve.

This chapter explained the current state of these assessment methods and identified a new trend toward more comprehensive accounting through LCA. A national average for the embodied carbon emissions of entire buildings (produced using EIO LCA) was identified as useful design data in the pre-design phase, while assembly specific data (produced using process-based LCA) is more appropriate for later in the design. It would be optimal to in some way combine these two approaches to LCA in order to capture the benefits of both.

The chapter also identified two major criticisms to the building environmental assessment methods. The first criticism was concerning a lack of absolute measure. This criticism was discussed via the critical review of three alternative methods to create such a measure. It was determined that each method has its own weakness. There is an uncomfortable amount of uncertainty in the approach of Olgyay and Herdt (2004); there is no clear scientific significance to the NZEB definition; and the IPCC approach relies on disputed average building emissions figures. The second criticism of building environmental assessment methods was regarding the design process aspect of assessment methods. This aspect is neglected in the development of assessment methodology. Any future suggestion for improvement to assessment methods should acknowledge these criticisms.

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8 http://kirkvalueplanners.com/

Chapter 4: Developing LCA data useful for assessing the carbon emissions of buildings

It was clear from Chapter 3 that national averages for the embodied carbon emissions of buildings per square foot would be useful design data. While this data exists in Japan, it does not yet exist for the US. Thus, chapter 4 presents new data to fill the gap in the US. Similar to how the data was produced for CASBEE, the US national averages are calculated using EIO LCA. By way of introduction to EIO LCA, this chapter first describes economic input-output economics and indicates how this approach could be used to assess environment impact. Next, the chapter describes EIO LCA of building construction currently being done in the United States. The chapter then presents new data on the embodied energy and carbon emissions of buildings, including validation with an earlier EIO LCA study, the process-based-LCA Athena EcoCalculator calculator (used by Green Globes), and the Japanese EIO-LCA data (used by CASBEE).

In addition, as discussed in chapter 3, it would be beneficial to in some way combine the EIO and process-based LCA approaches to inform building design decisions. Thus, the final section of chapter 4 describes hybrid EIO LCA and process-based LCA approaches that can be utilized by US building environmental assessment methods.

4.1 Origins of EIO LCA

4.1.1 Introduction to input-output economics

German-American Wassily Leontief conceived economic input-output analysis. A Harvard professor, he won the Nobel Prize for his publication of *Input-Output Economics* in 1966. It is a simple framework of economic analysis that has proven to be a powerful tool for predicting economic flows. Next to the Gross Domestic Product, the Input-Output (IO) tables provide the fundamental framework for the work of the Bureau of Economic Analysis (BEA). An agency in the US Department of Commerce, the BEA uses IO tables to present "inter-industry relationships" and other aspects of the US economy.[9]

An IO table is a matrix that represents the flow of dollars from economic sector to sector. The formation of the table relies on US Census Bureau data that details the purchases and sales of each economic sector (BEA 2006). Leontief best explains the foundational table as follows:

> Consider a simple economy consisting of two producing sectors, say, Agriculture and Manufacture, and Households. Each one of the two industries absorbs some of its annual output itself, supplies some to the other industry and delivers the rest to the final consumers—in this case represented by the Households. These inter-sectoral flows can be conveniently entered in an input-output table. For example:

TABLE 1. — INPUT-OUTPUT TABLE OF A NATIONAL ECONOMY (IN PHYSICAL UNITS)

Into / From	Sector 1 Agriculture	Sector 2 Manufacture	Final Demand Households	Total Output
Sector 1 Agriculture	25	20	55	100 bushels of wheat
Sector 2 Manufacture	14	6	30	50 yards of cloth

Leontief 1970, p 262

The US economy-wide equivalent to Leontief's table above (in units of US currency) is available from the BEA. It is called the "Use" table. The rows are the commodities produced and the columns are the industries that *use* them. In Leontief's example, notice that Sector 1 Agriculture "purchased" commodities from itself (25 bushels of wheat) as well as from Sector 2 Manufacture (14 yards of cloth). It produced 100 bushels of wheat for itself (25 bushels), Manufacture (20

[9] Bureau of Economic Analysis www.bea.gov

bushels), and Households (55 bushels). While it was clear before EIO analysis that in order to produce commodities each economic sector must purchase commodities, Leontief's tables concisely and comprehensively present these required purchases (i.e., the indirect purchases) like nothing before.

EIO analysis reveals the interdependencies of the economic sectors. Each coefficient in the BEA "Industry by Commodity Total Requirements" table shown below (Figure 4-7) represents the required dollar amount of each commodity (rows) in order to for an industry (columns) to produce \$1.00 of commodity. For instance, \$0.01150 of Sector 1120 "Animal products" must be consumed in order for Sector 1110 "Crop products" to produce \$1.00 output.

Table 4-12. Sample of the 1997 Industry by Commodity total requirements matrix from the BEA. The table, a 492×492 matrix, identifies the inputs of commodities (rows) required by industries (columns) in 1997 dollars to produce one dollar of industry output.

Industry by Commodity Total Requirements after Redefinitions, 1997

		Crop products	Animal products	Forestry and logging products	Fish and other nonfarm animals	Agriculture and forestry support services	Oil and gas	Coal	Metal ores	Nonmetallic minerals	Mining support services	Electric power
PubCode	indLabel	1110	1120	1130	1140	1150	2110	2121	2122	2123	2130	2211
1110	Crop production	1.07234	0.36565	0.03508	0.03107	0.20841	0.00068	0.00096	0.00133	0.00104	0.00120	0.00118
1120	Animal production	0.01159	1.25805	0.03255	0.02250	0.15045	0.00036	0.00053	0.00085	0.00066	0.00066	0.00082
1130	Forestry and logging	0.00349	0.00318	1.39466	0.00292	0.00488	0.00085	0.00290	0.00228	0.00127	0.00155	0.00237
1140	Fishing, hunting and trapping	0.00008	0.00181	0.00011	1.05609	0.00029	0.00003	0.00004	0.00010	0.00007	0.00006	0.00012
1150	Agriculture and forestry support activities	0.06064	0.04052	0.12933	0.11931	0.85607	0.00014	0.00035	0.00032	0.00021	0.00025	0.00032
2110	Oil and gas extraction	0.03577	0.03479	0.01443	0.04602	0.02254	1.15029	0.02932	0.04499	0.05180	0.04386	0.09084
2121	Coal mining	0.00209	0.00393	0.00072	0.00086	0.00153	0.00253	1.09395	0.00691	0.00715	0.00299	0.06889
2122	Metal ores mining	0.00113	0.00097	0.00036	0.00051	0.00081	0.00129	0.00147	1.09782	0.00172	0.00176	0.00080
2123	Nonmetallic mineral mining and quarrying	0.00777	0.00405	0.00127	0.00228	0.00568	0.00134	0.05169	0.00528	1.00678	0.00596	0.00454
2130	Support activities for mining	0.00083	0.00081	0.00031	0.00094	0.00054	0.02239	0.02209	0.01314	0.01233	0.99610	0.00314
2211	Power generation and supply	0.01992	0.03390	0.00678	0.00749	0.01472	0.02314	0.02643	0.07059	0.04249	0.01390	0.87217
2212	Natural gas distribution	0.00422	0.00410	0.00498	0.00208	0.00292	0.00695	0.00208	0.00258	0.00368	0.00394	0.00201
2213	Water, sewage and other systems	0.00120	0.00088	0.00012	0.00019	0.00034	0.00022	0.00012	0.00012	0.00016	0.00025	0.00036
2301	New residential construction	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2302	New nonresidential construction	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2303	Maintenance and repair construction	0.00905	0.01144	0.00257	0.06415	0.00647	0.00319	0.00386	0.00507	0.00430	0.00607	0.02343
3110	Food manufacturing	0.00658	0.26712	0.01424	0.01125	0.03835	0.00131	0.00165	0.00305	0.00229	0.00223	0.00301
3121	Beverage manufacturing	0.00015	0.00124	0.00011	0.00992	0.00030	0.00009	0.00018	0.00028	0.00022	0.00022	0.00032
3122	Tobacco manufacturing	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3130	Textile mills	0.00315	0.00316	0.00243	0.00561	0.01254	0.00083	0.00274	0.00169	0.00139	0.00125	0.00101
3140	Textile product mills	0.00318	0.00315	0.00374	0.01101	0.02368	0.00026	0.00057	0.00058	0.00043	0.00040	0.00045
3150	Apparel manufacturing	0.00032	0.00041	0.00029	0.00071	0.00138	0.00012	0.00031	0.00019	0.00017	0.00022	0.00019
3160	Leather and allied product manufacturing	0.00027	0.00095	0.00022	0.00038	0.00076	0.00018	0.00027	0.00022	0.00026	0.00030	0.00018
3210	Wood product manufacturing	0.00837	0.00745	0.00318	0.00698	0.00350	0.00174	0.00553	0.00628	0.00262	0.00390	0.00749
3221	Pulp, paper, and paperboard mills	0.00424	0.00838	0.00184	0.00367	0.00373	0.00358	0.00452	0.00535	0.00520	0.00556	0.00528
3222	Converted paper product manufacturing	0.00642	0.01416	0.00215	0.00329	0.00496	0.00318	0.00397	0.00442	0.00400	0.00418	0.00333
3230	Printing and related support activities	0.00471	0.00778	0.00253	0.00375	0.00478	0.00433	0.00502	0.00534	0.00581	0.00954	0.00552
3240	Petroleum and coal products manufacturing	0.04107	0.04202	0.01582	0.06646	0.02227	0.01888	0.03806	0.04568	0.05745	0.04370	0.02551
3251	Basic chemical manufacturing	0.03558	0.02158	0.00968	0.01130	0.03074	0.02088	0.01186	0.02659	0.01794	0.02072	0.00790
3252	Resin, rubber, and artificial fibers manufacturing	0.00525	0.00603	0.00389	0.00445	0.00788	0.00390	0.00652	0.00841	0.00533	0.00471	0.00293
3253	Agricultural chemical manufacturing	0.11053	0.04851	0.01841	0.01723	0.11672	0.00047	0.00046	0.00074	0.00052	0.00067	0.00053
3254	Pharmaceutical and medicine manufacturing	0.00058	0.00563	0.00032	0.00034	0.00123	0.00035	0.00018	0.00022	0.00018	0.00024	0.00024
3255	Paint, coating, and adhesive manufacturing	0.00093	0.00137	0.01105	0.00137	0.00090	0.00081	0.00144	0.00166	0.00144	0.00156	0.00170
3256	Soap, cleaning compound, and toiletry manufacturing	0.00299	0.00277	0.00075	0.00222	0.00310	0.00063	0.00080	0.00098	0.00086	0.00367	0.00049
3259	Other chemical product and preparation manufacturing	0.00300	0.00544	0.00292	0.00194	0.00274	0.00861	0.01717	0.02291	0.01418	0.01243	0.00425
3260	Plastics and rubber products manufacturing	0.01201	0.01839	0.00591	0.00803	0.00827	0.01008	0.02465	0.02944	0.01686	0.01202	0.00874
3270	Nonmetallic mineral product manufacturing	0.00551	0.00643	0.00169	0.00524	0.00340	0.00739	0.01016	0.01353	0.04379	0.02196	0.00969
331A	Iron and steel mills and forming steel products	0.01119	0.00974	0.00259	0.00475	0.00472	0.02376	0.02507	0.02970	0.01577	0.03302	0.00879
331B	Nonferrous metal production and processing	0.00405	0.00577	0.00190	0.00324	0.00302	0.00483	0.00787	0.01026	0.00589	0.00764	0.00713
3315	Foundries	0.00141	0.00208	0.00077	0.00100	0.00091	0.00196	0.00437	0.01618	0.00326	0.00280	0.00168
3321	Forging and stamping	0.00099	0.00190	0.00056	0.00081	0.00094	0.00118	0.00253	0.00898	0.00208	0.00186	0.00156
3322	Cutlery and handtool manufacturing	0.00192	0.00313	0.00040	0.00034	0.00091	0.00027	0.00050	0.00051	0.00038	0.00036	0.00043
3323	Architectural and structural metals manufacturing	0.00250	0.00348	0.00071	0.00305	0.00144	0.00313	0.00621	0.00614	0.00731	0.01383	0.00500

4.1.2 Producing the Industry by Commodity matrix

The mathematical derivation of the Industry by Commodity matrix requires linear-algebraic gymnastics that are out of the scope of this thesis. Appendix A provides this derivation, which was produced by the BEA. However, for this thesis it is important to understand the basic logic.

The BEA begins with "Make" and "Use" tables that document every dollar of commodity an industry makes and every dollar of commodity it uses.[1] This accounting is done every few years and this thesis references the latest account, which is from 1997.[2] The Make and Use tables are 492×492 matrices and are defined as W and U (see Appendix A). The 492 industries and the 492 commodities in the US economy are all taken into account.

Some characteristics of this data are worth noting. First, the industries have the same sector definition as the commodities. For instance, sector 1110 "Crop production" represents an industry as well as a commodity. Second, not all commodities are produced by industries of the same sector. For instance, in 1997 about 1 percent of sector 1110 production was a sector 1150 "Agriculture and forestry support services" commodity (BEA 1997). Indeed, industry sector 3256 "Soap, cleaning compound, and toiletry manufacturing" produced commodities in over 10 commodity sectors ranging from "New residential construction" (2302) to "Petroleum and coal products" (3240). As a final note, despite industries producing commodities in several sectors, the commodities produced outside of the industry's own sector typically represent less than 5 percent of the industry's total commodity production.

The matrix W shows where the commodities are coming from. The columns are commodities and the rows are industries. By choosing a commodity and moving down the column,

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[1] These tables can be accessed at the BEA Industry Economic Accounts website at http://www.bea.gov/industry/io_benchmark.htm#1997data, "Summary Tables."

[2] During the writing of this thesis, the BEA released its 2002 account.

one can observe all the industries that are contributing (and by how much) to the total output of that commodity.

The matrix U displays where the commodities are going. The columns are industries and the rows are commodities. So by choosing an industry and moving down the column, one can observe all the commodities that it uses to produce its total amount of production (or total industry output, which can be commodities in the same or a separate sector, as discussed above). Through algebraic manipulation described in Appendix A, the values within this matrix are converted to show the commodities used per dollar of industry output. This new matrix is defined B, and will later be referred to as the *direct requirements matrix* because it shows the commodities an industry purchases *directly* for one dollar of output.

As shown in Appendix A, the Industry by Commodity total requirements matrix is a function of B, W, and the identity matrix I. The total requirements matrix is so named because it not only displays the direct purchases of commodities made by an industry to produce a commodity (i.e., the direct requirements matrix displays this) but also the purchases of those industries that produced said commodities, the purchases of those industries, and so on. For instance, the Crop production industry makes no direct purchase from sector 2121 Coal mining (see BEA 1997) but purchases $0.00209 per dollar output according to the total requirements table (see Figure 4-9).

4.1.3 Assessing environmental effect

EIO analysis lends itself well to the assessment of environmental effect. According to Leontief in 1970:

> The quantity of carbon monoxide released in the air bears, for example, a definite relationship to the amount of fuel burned by various types of automotive engines; the discharge of polluted water into our streams and lakes is linked directly to the level of output

of the steel, the paper, the textile and all the other water-using industries and its amount depends, in each instance, on the technological characteristics of the particular industry.

Leontief 1970, p 262

Relying on this framework set forth by Leontief himself, Richard G. Stein et al (1981) completed a major EIO LCA study of the energy used in the building sector. This study, accomplished with the Department of Energy and based on 1967 data, was the first EIO LCA of the building sector and perhaps any sector. The resultant "Handbook of Energy Use for Building Construction" presents a very detailed report of the embodied energy of not only individual building materials but also building assemblies and the buildings themselves on a square foot basis.

4.2 EIO LCA in the United States

4.2.1 Overview

There is active EIO LCA research in at least the United States and other parts of the world. In the US, a team at Carnegie Mellon University (CMU) leads the research efforts (Hendrickson et al 2006). Only a few studies have been made with a particular focus on building construction (Ochoa et al 2002, Junnila et al 2006, Sharrard 2007). Given that the studies do not cite the work of Stein et al, these researchers must be unaware of this nearly three-decade-old contribution. The greatest fruit of the CMU team's labor is the online calculator hosted at its Green Design Institute website.[3] Data from this calculator is showing up in carbon footprint calculators on the web[4] and researchers in a variety of fields (not just building construction) use it nearly every day.[5]

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[3] EIO LCA homepage. http://www.eiolca.net

[4] The Berkeley Institute of the Environment. http://coolclimate.berkeley.edu/

[5] EIO LCA Forum. http://www.eiolca.net/forum/phpBB2/

The calculator database includes an environmental effect coefficient, as shown in Table 4-4, for each economic sector. These coefficients were derived from "a variety of sources" but for many sectors the process can be generalized into three basic steps (Sharrard 2007, p 76). First, direct requirements (in US dollars) of each sector on "Coal" (sector 212100), "Natural gas distribution" (sector 221200), "Power generation and supply" (sector 221200) and "Petroleum refineries" (sector 324110) are determined from the BEA's 1997 "Use of commodities by industries" table. For instance, sector 2301 "New residential construction" purchased $177,400 from sector 2212 "Natural gas distribution" for its total industry output of $230,999,700 (BEA 1997). Second, these prices are converted to physical units based on price rates for the year 1997. Third, in the case of carbon dioxide emissions for example, the physical unit of natural gas or other is converted to carbon dioxide emissions using standard emissions factors.

I-O Sector		Metric Tons / Million $				
21e	Description	GWP	CO_2	CH_4 (CO_2Eq)	N_2O (CO_2Eq)	HFCs (CO_2Eq)
230110	New residential 1-unit structures, nonfarm	211	211	-	-	-
230120	New multifamily housing structures, nonfarm	259	259	-	-	-
230130	New residential additions and alterations, nonfarm	238	238	-	-	-
230140	New farm housing units and additions and alterations	218	218	-	-	-
230210	Manufacturing and industrial buildings	109	109	-	-	-
230220	Commercial and institutional buildings	152	152	-	-	-
230230	Highway, street, bridge, and tunnel construction	400	400	-	-	-
230240	Water, sewer, and pipeline construction	374	374	-	-	-
230250	Other new construction	368	368	-	-	-
230310	Maintenance and repair of farm and nonfarm residential structures	238	238	-	-	-
230320	Maintenance and repair of nonresidential buildings	226	226	-	-	-
230330	Maintenance and repair of highways, streets, bridges, and tunnels	390	390	-	-	-
230340	Other maintenance and repair construction	373	373	-	-	-

Table 4-13. Some values in the environmental effect vector. This table from Sharrard (2007) only includes the construction sectors.

The CMU tool calculates the total (direct and indirect) environmental impact of a purchase from one sector in an economy. Users select a model (ones for US, Canada, Germany and Spain are available), a sector (e.g., sector 23022 "Commercial and institutional buildings"), the amount of economic activity (i.e., the purchase amount), and the category of results (e.g., Pollutants, Greenhouse gasses, toxic releases). The calculation is as follows:

$$B = R(Xy)$$

Where:

B = Total environmental effect. This is a single value product of the multiplication of two vectors.

R = Environmental effect matrix. This is a 492×492 matrix with the environmental effect coefficients for each sector along the diagonal and zeros elsewhere. See Table 4-4 below for example units.

X = Industry by Commodity total requirements table. This is a 492×492 matrix as shown in Figure 4-9.

y = Final demand vector. This is a 1×492 vector of all zeros except one value, which is the purchase (or economic activity) being environmentally assessed.

4.2.2 Creating a Custom Model

It is possible to use CMU's EIO LCA tool to create a model of a customized economic sector. This is useful for changing the boundary of the life cycle assessment. For example, for the assessment of commercial building construction, the EIO LCA model of Sector 230101 "Nonresidential commercial and health care structures" covers everything from structural materials to furniture to design services for the building. However, an analyst may want to know the environmental impact of only the building structure (not finish materials or furniture).

In order to change the analysis boundary of the EIO LCA, users can access the *direct requirements vector* for the chosen sector in the CMU calculator.[6] The direct requirements vector is the one column in the direct requirements matrix (defined in section 4.1.2) that represents the chosen sector. That is, it is a list of all the direct purchases made by the chosen sector in order to produce its industrial output.

The analysis boundary can be reduced by zeroing-out the direct purchases that are outside the desired boundary analysis. For example, the 1997 EIO LCA commercial and institutional buildings sector makes direct purchases from nearly all of the US sectors. If one wanted to limit the boundary of analysis to only the structural materials, then the direct purchases in economic sectors that are not structural (such as Sector 327211 "Flat glass manufacturing") should be made zero.

When the direct requirements vector is altered, the sector is effectively split in two (Hendrickson et al 2006). One part is the sector that is defined by the user. The other part is the effect of balancing the rest of the matrix. The CMU tool automatically balances the matrix after the direct requirements vector is altered.

4.3 Determining the energy and carbon emissions intensity of building construction

4.3.1 Note on accuracy

It should be noted up front that any EIO LCA results should include only one or two significant figures (Hendrickson et al 2006). Thus, the purpose of determining the energy and carbon emissions intensity of building construction is not meant to be precise, but rather an estimate that provides a general sense of the environmental impact.

[6] Use the CMU tool at http://www.eiolca.net and click the option for "Create custom model" then "Hybrid product" to choose a sector and view its direct requirements. [accessed December 2009]

4.3.2 Method

The CMU tool was used to determine the energy and carbon emissions per dollar spent for four building construction types, as shown in Table 4-5. In order to convert the denominator of these coefficients from dollars to square feet, the total square footage and dollar amount of construction needed to be determined for 1997. Construction starts in 1997 was obtained from the McGraw-Hill Companies, Inc. The categories of this data were several and required mapping to one of the four IO sectors of Table 4-5. For instance, the McGraw-Hill categories "Offices and Bank Buildings" as well as "Hotels and Motels" should both be included in IO sector 23022, "Commercial and Institutional Buildings." The entire map can be found in Appendix B. Table 4-6 shows the results of this exercise to re-categorize the McGraw-Hill data. The total economic outputs of each construction sector, also shown in Table 4-6, were determined from the BEA's 1997 Benchmark IO Item Output table.

EIO LCA Sector		Energy intensity (TJ/million USD)	Carbon intensity (MT CO_2e/million USD)
23011	1-unit Residential	6.8	563
23012	Multifamily	7.9	640
23021	Manufacturing and industrial buildings	7.63	588
23022	Commercial and institutional buildings	7.72	599
Source:	Carnegie Mellon University Green Design Institute. (2008) Economic Input-Output Life Cycle Assessment (EIO-LCA), US 1997 Industry Benchmark model [Internet], Available from:<http://www.eiolca.net> Accessed 1 January, 2008.		

Table 4-14. EIO LCA factors for building construction based on the US economy in 1997.

EIO LCA Sector		Total industry output (million USD)	Area of Construction Starts (1000 ft²)
23011	1-unit Residential	172,489	2,182,072
23012	Multifamily	26,234	403,362
23021	Manufacturing and industrial buildings	27,487	327,815
23022	Commercial and institutional buildings	190,818	958,231
Source:		Bureau of Economic Analysis, 1997 IO Item Output	McGraw-Hill Construction

Table 4-15. 1997 characteristics of I-O sectors in the US economy.

4.3.3 Results and validation

Two simple calculations were made using the data in Tables 4-14 and 4-15 to determine the carbon and energy intensities presented in Table 4-16. First, the total industry outputs in each EIO LCA Sector were multiplied by the energy and carbon intensity factors. This calculation determined the total energy and carbon from each EIO LCA Sector. These total values were then divided by the total square feet of construction starts for 1997.

It is important to validate the intensity numbers with other studies. The energy intensity values can be compared to the only other EIO LCA study of a US economy, the "Handbook of Energy Use for Building Construction" by Stein et al (1981) as well as the CASBEE data. After a modification to the EIO LCA boundary of analysis, the values can also be compared to the Athena EcoCalculator.

EIO LCA Sector		Energy intensity (kBtu/ft²)	Carbon Intensity (kg CO_2e/ft²)
23011	1-unit Residential	510	45
23012	Multifamily	490	42
23021	Manufacturing and industrial buildings	610	49
23022	Commercial and institutional buildings	1500	120

Table 4-16. Energy and carbon intensity for building construction sectors.

4.3.3.1 Historical Comparison to "Handbook of Energy Use for Building Construction"

The classic DOE "Handbook of Energy Use for Building Construction" (Stein et al 1981) utilized an EIO LCA method to produce estimates of the embodied energy of building construction (embodied energy of materials and energy used on site) per square feet of new construction starts, based on 1967 data. In order to compare this data to the 1997 energy intensities, the results from the several building construction sectors of the 1967 US economy (the "Handbook sectors") were aggregated into the four 1997 EIO LCA sectors listed in Table 4-7. After this aggregation, the total energy consumed in 1967 within each of the four EIO LCA sectors was divided by the total square footage to obtain the energy intensity. As shown in Appendix C, this calculation produces the average 1967 energy intensity for each of the four EIO LCA sectors. For instance, EIO sector 23021 "Manufacturing and industrial buildings" included two Handbook sectors: Industrial buildings (Sector 30) and Warehouses (Sector 32), each of which have an energy intensity (983,697 and 566,071 Btu/ft^2, respectively) and an amount of 1967 construction starts (476,468,000 and 103,468,000 ft^2, respectively). The energy intensity for Sector 23021 is the averaged energy intensity of Sectors 30 and 32, weighted by the construction starts, which equals 909,000 Btu/ft^2.

According to the results displayed by Figure 4-10, the energy intensity of building construction has decreased since 1967 for three of the four analyzed sectors. New residential 1-unit, new multifamily, and manufacturing and industrial structures each decreased by 30 +/- 3%. The outlier was commercial and institutional buildings which actually increased by 15%.

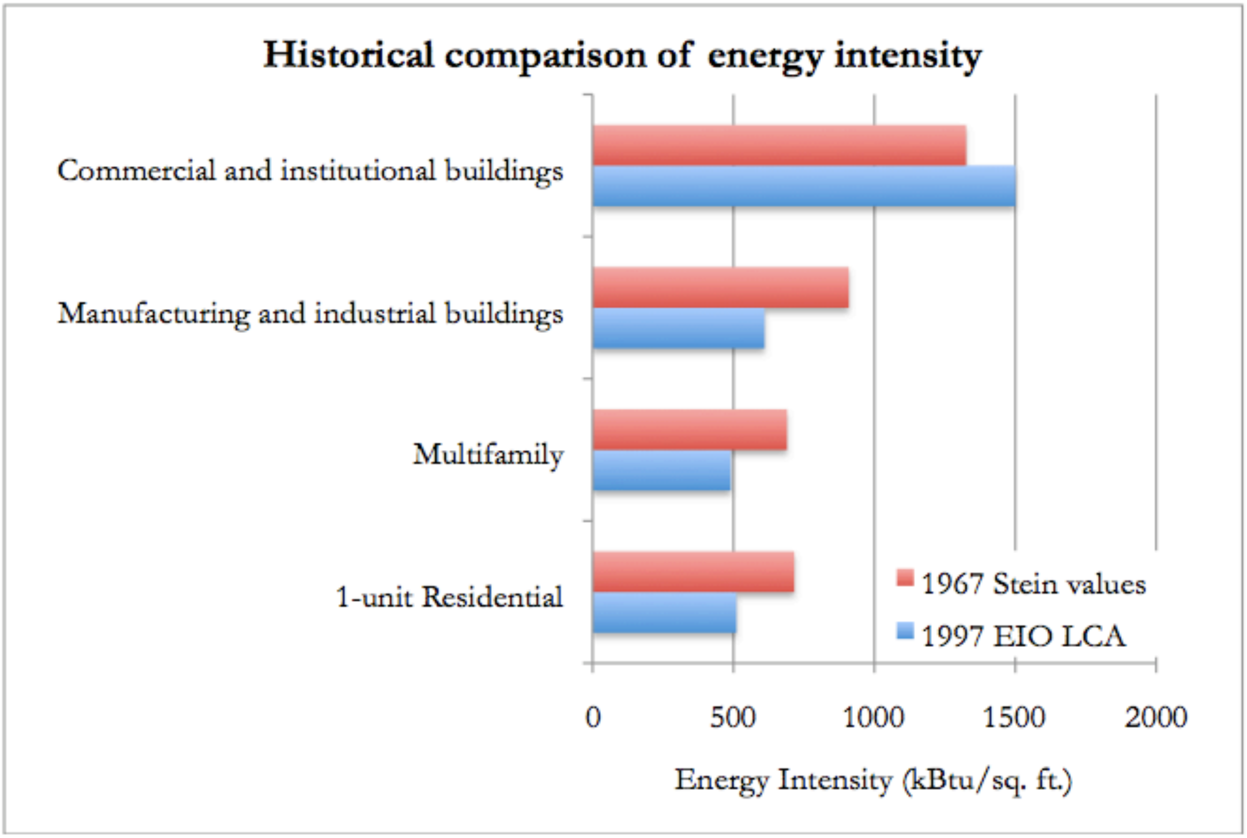

Figure 4-1. Historical comparison between Stein et al (1981) and 1997 construction energy intensity.

Given a general trend of decreasing energy and carbon intensity per GDP in the US, it was expected that the embodied energy of building construction would decrease over the three decades between the 1967 Stein values and the 1997 EIO LCA results. Since 1980, the energy and emissions intensity has been cut almost in half (see Figure 4-11). It is somewhat surprising that the commercial and institutional building sector would not decrease about 30% like the other sectors. A different mix of materials going into those buildings could explain the disparity. For instance, there was likely a large increase in energy-intensive glazing (including double-skinned facades) between 1967 and 1997. In addition, highly energy-intensive steel and concrete as opposed to wood or stone structural materials have become more common.

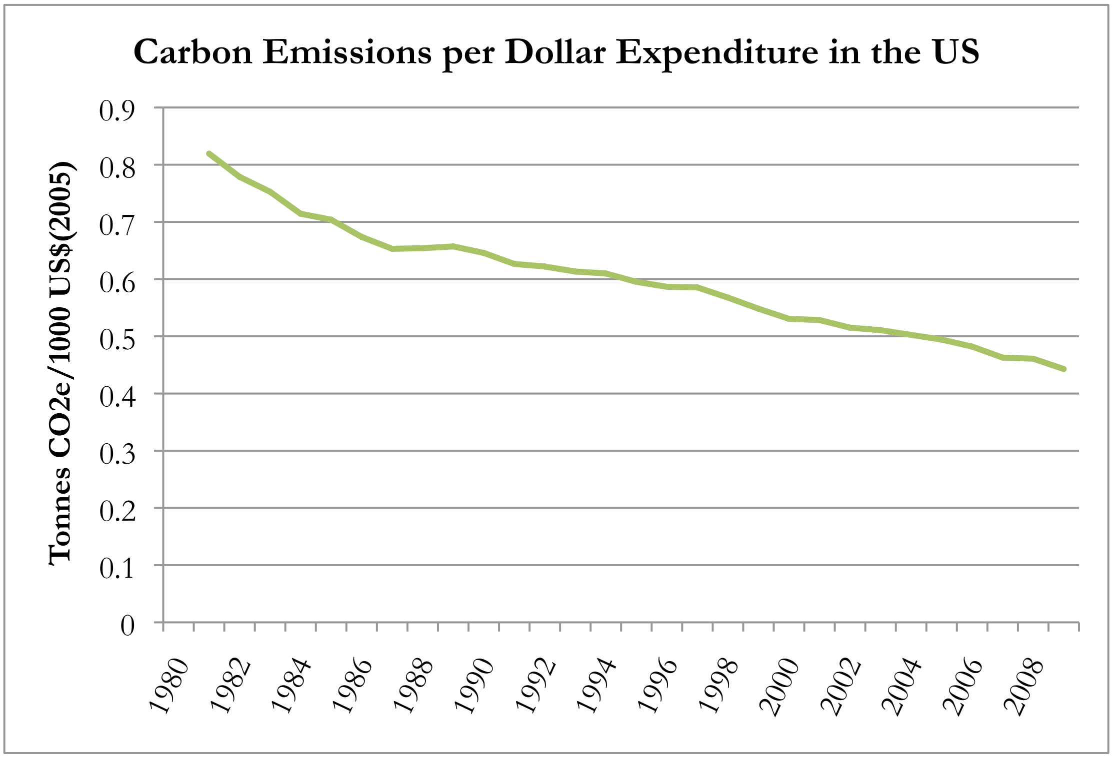

Figure 4-2. The carbon intensity of the GDP has been steadily decreasing. Source: US Energy Information Administration

There was a source of error in aggregating the 1967 Handbook sectors into the four 1997 EIO LCA sectors. One sector in particular, Handbook Sector 38 "Other non-farm buildings," could have been included in either EIO LCA sectors 23021 (Manufacturing and industrial buildings) or 23022 (Commercial and institutional buildings). In fact, it is possible that a percentage of Sector 38 (159,483,000 ft^2 of construction starts at 147 $kBtu/ft^2$) belongs in each one. Thus, the errors of the 1967 energy intensity estimates for 23021 and 23022 can be estimated by calculating the range between including and not including the entire Sector 38. A mid-point value and the percent increase or decrease to reach the high and low values were calculated. This simple analysis indicates that including 100 percent of Sector 38 in either 23022 or 23021 would not flip the results displayed in Figure 4-10; that is, the 1967 estimate of 23022 will remain smaller than the 1997 estimate, and the 1967 23021 estimate will remain larger than the 1997 estimate.

EIO LCA Sector		1967 EIO LCA sector "mid"estimate (kBtu/ft^2)	Error (+/–)	Percent difference from 1997 EIO LCA sector estimate
23022	Commercial and institutional buildings	1240	7%	–21%
23021	Manufacturing and industrial buildings	827	10%	+26%

Table 4-17. Error analysis of 1967 and 1997 EIO LCA comparison. Half of the Handbook sector 38 was added to sectors 23022 and 23021 to produce the "mid" estimate. Since the absolute value of the error is less than the percent difference from 1997 EIO LCA sector, the conclusion of the analysis does not change.

4.3.3.2 Comparison to Japanese EIO LCA data

The comparison of the average 1997 US EIO LCA value to the average carbon emissions intensity values used in CASBEE reveals that the Japanese economy is in general more efficient at building construction than the US economy. This might be expected as cement and other heavy-duty construction trucks in Japan are likely more fuel-efficient than the ones in America. In addition, materials do not have to travel as far, given the size of Japan relative to the US. And finally, imported materials likely come on a boat from neighboring countries, which is a low energy mode of travel and a short distance.

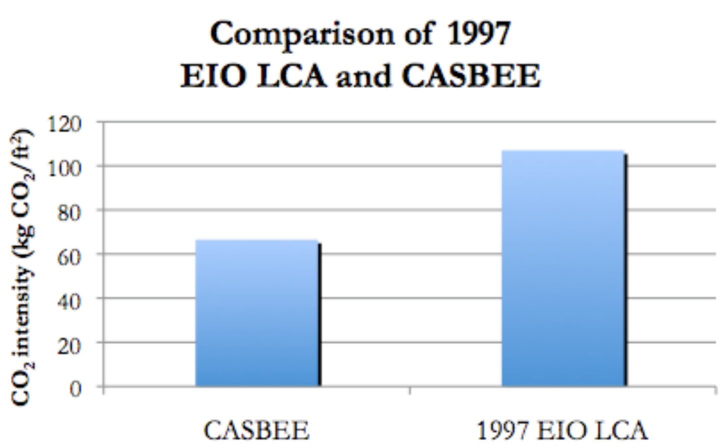

Figure 4-3. Comparison of 1997 EIO LCA carbon intensity values to CASBEE.

4.3.3.3 Comparison to EcoCalculator

The 1997 EIO LCA value for sector 23022 Commercial and institutional buildings cannot be directly compared to the EcoCalculator values. This is because the EIO LCA boundary of analysis covers everything from the building structure to the furniture inside the constructed building, while the EcoCalculator only accounts for the structure and basic finishes such as drywall and paint (but not HVAC or lighting equipment, etc). In addition, the EcoCalculator output is not an average energy or carbon emissions per square foot of building construction; rather, it is the energy and carbon emissions associated with the construction a particular building.

However, the values can be compared with some adjustments. First, the boundary of the EIO LCA analysis is narrowed to that of the EcoCalculator. Second, a typical commercial building is assessed using EcoCalculator to obtain an average energy and carbon emissions per square foot of building construction. After taking these two steps, the outputs from both EIO LCA and EcoCalculator approaches are assessing the same thing: the average energy and carbon emissions of building construction, including the structure and basic finishes. The EIO LCA and Green Globes results are within 17% of each other.

Before a typical commercial building can modeled in EcoCalculator, characteristics of such a building must first be determined. The characteristics of the typical commercial building are determined from data in the DOE Buildings Data Book[7]. According to Table 3.7.5 in the Data Book, there are typical large and small mercantile & service buildings. Selected data from this table is reproduced in Table 21 below. The Buildings Data Book provides similar data for schools, hospitals, and office buildings.

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[7] Accessed online at http://buildingsdatabook.eren.doe.gov/ in November 2010.

	Stock floor area (billion ft^2)	Floor-area weighted averages (1000 ft^2)	Floors	Shell Percent Glass
Large (>25,000 ft^2)	5.88	80	2	15
Small (<25,000 ft^2)	6.53	5.3–6.4	1	15

Table 4-18. Selected data about for a typical mercantile & service building from DOE Buildings Data Book.

Unfortunately, data for typical buildings has not been produced for all types of commercial buildings. The DOE Buildings Data Book only covers slightly more than half of the entire building stock as shown in Figure 4-4.

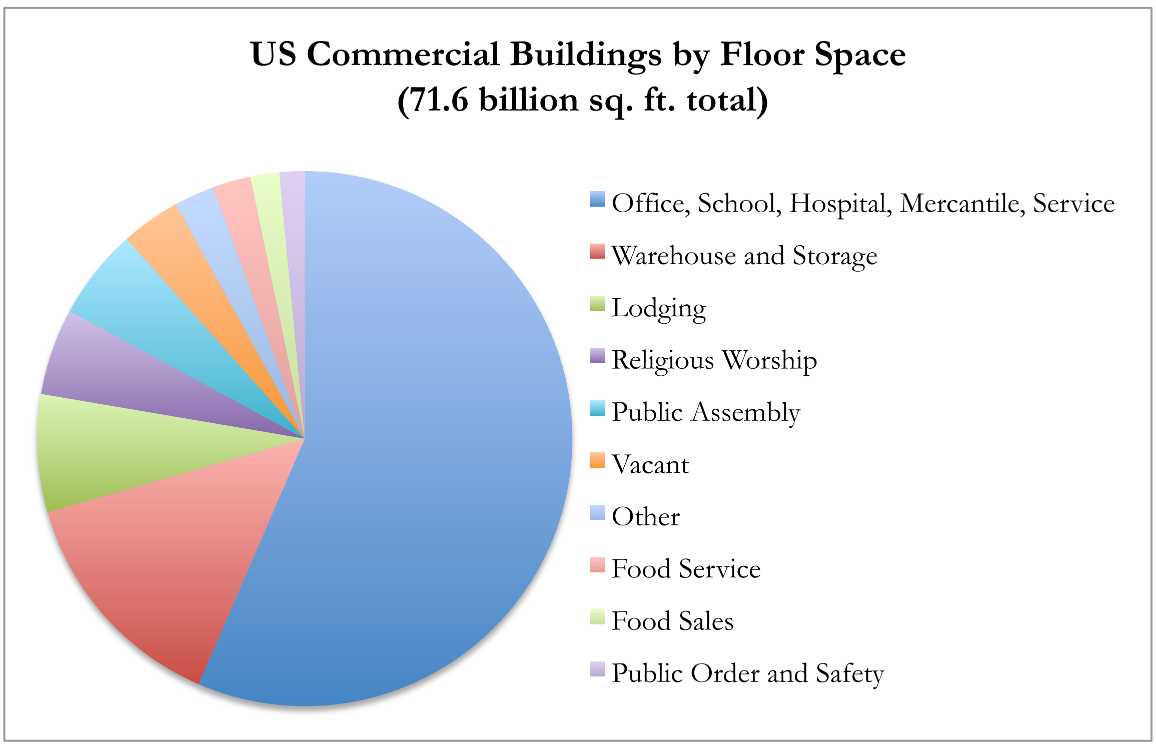

Figure 4-4. Commercial buildings by floor space. Source: US EIA CBECS Table A4.

Nonetheless, the typical building characteristics for schools, hospitals, offices, and mercantile & service buildings are used to determine a typical commercial building. The weighted-average floor areas, floors, and shell percent glass are shown in Table 4-19.

	Floor-area weighted average (1000 ft^2)	Floors	Shell Percent Glass
Typical commercial building	42	2.8	26

Table 4-19. Typical commercial building data.

Data for the typical commercial building is now entered into the EcoCalculator. The energy and carbon emissions assessment results are displayed in Table 4-20. The theoretical commercial building has 2.8 floors, a total of 42,000 gross square feet (thus, a 15,000 square foot roof), and 26 percent of the exterior walls are windows. The building is assumed to have a cube shape with 15-foot stories, thus total exterior wall area is 11,000. Interior walls were estimated to be 10,000.

Inputs to EcoCalculator		**EcoCalculator Data**		**Outputs from EcoCalculator**	
Assembly category	Area (ft^2)	Primary Energy Intensity ($MMBtu/ft^2$)	Carbon Emissions Intensity (lbs CO_2e /ft^2)	Total Energy (kBtu)	Total Carbon Emissions (t CO_2e)
Floors	42,000	0.07	10.77	2,900,000	200
Exterior walls	11,000	0.14	22.25	1,500,000	110
Interior walls	10,000	0.06	6.85	600,000	31
Windows	2,900	0.61	95.74	1,800,000	130
Roofs	15,000	0.24	22.34	3,600,000	150
			Total:	10,000,000	620
			Intensity:	$kBtu/ft^2$	kg CO_2e/ft^2
				240	15

Table 4-20. The carbon and energy intensity of a building was calculated using the EcoCalculator.

Next, a custom EIO LCA model that matches the EcoCalculator boundary of analysis was created. Table 4-10 displays which sectors were selected to represent the EcoCalculator boundary of analysis.

I-O Number	Name	USD input/1000 USD output
113300	Logging	0.003
230320	Maintenance and repair of nonresidential buildings	1.233
321113	Sawmills	5.744
321114	Wood preservation	2.737
321219	Reconstituted wood product manufacturing	1.29
32121A	Veneer and plywood manufacturing	3.922
32121B	Engineered wood member and truss manufacturing	3.922
321911	Wood windows and door manufacturing	6.704
321992	Prefabricated wood building manufacturing	3.253
321999	Miscellaneous wood product manufacturing	0.34
3221A0	Paper and paperboard mills	0.603
324122	Asphalt shingle and coating materials manufacturing	1.89
327121	Brick and structural clay tile manufacturing	0.9
32721A	Glass and glass products, except glass containers	4.331
327310	Cement manufacturing	2.229
327320	Ready-mix concrete manufacturing	8.064
327331	Concrete block and brick manufacturing	2.218
327390	Other concrete product manufacturing	3.048
327420	Gypsum product manufacturing	2.944
331111	Iron and steel mills	0.377
331222	Steel wire drawing	1.137
332111	Iron and steel forging	0.005
332311	Prefabricated metal buildings and components	4.842
332312	Fabricated structural metal manufacturing	15.036
332321	Metal window and door manufacturing	9.284
420000	**Wholesale trade**	**26.747**
481000	**Air transportation**	**1.949**
482000	**Rail transportation**	**1.167**
483000	**Water transportation**	**0.295**
484000	**Truck transportation**	**9.391**
4A0000	**Retail trade**	**46.501**

Table 4-21. Sectors chosen to represent the EcoCalculator boundary of analysis. Sectors in bold were not completely included inside the boundary.

It was not clear what percentage of the transportation and trade sectors should be included in the EcoCalculator boundary of analysis. The transportation sector represents the transportation of all materials to the site. Since the number of materials is being limited according to the sectors listed in Table 4-10, the current transportation sector estimate is likely too high. Also, the trade sectors represent the materials used for the building that are not produced domestically and it is not clear which of these imported materials fall within the EcoCalculator boundary of analysis.[8] To resolve these uncertainties, it was assumed that materials in the EcoCalculator boundary of analysis equal half of all economic flow through the transportation and trade sectors. This assumption introduced minor error (4 percent).[9]

As a result of decreasing the boundary of analysis, the EIO LCA estimate of energy consumption and carbon emissions per square foot of building construction is only 21% and 20% of energy and emissions of the total. This result will be useful for developing a hybrid model in the following section.

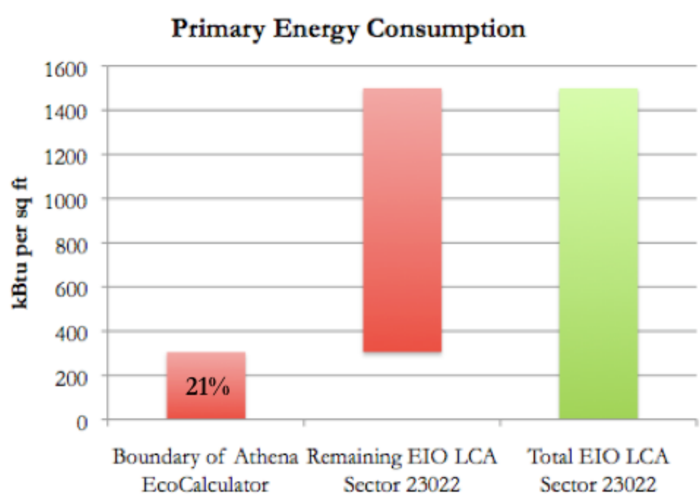

Figure 5. Percent of total EIO LCA boundary covered by Athena EcoCalculator, primary energy consumption.

[8] The EIO LCA calculator estimates that the energy and emissions intensity of imported materials is the same as that of domestically produced materials.
[9] Error estimate is based on the change in the amount of energy if the entire flow through the trade and transportation sectors is included or not.

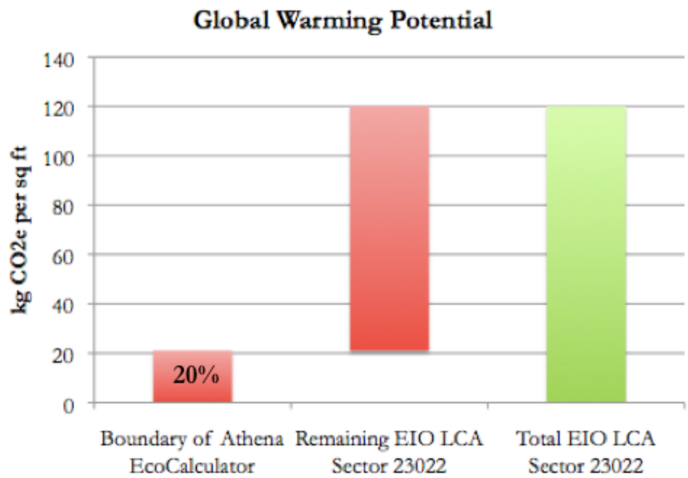

Figure 6. Percent of total EIO LCA boundary covered by Athena EcoCalculator, carbon emissions.

The tables below show the results of the boundary-adjusted EIO LCA estimate and the typical-building EcoCalculator estimate. Unlike the comparison to the Stein et al (1981) study, these estimates are of the same economy and the estimates should be the same. For energy and emissions, the EIO LCA estimate is 17% and 10% less than the EcoCalculator, respectively. This difference can be attributed to error in building a “typical” building in the EcoCalculator and the EIO LCA boundary of analysis adjustment.

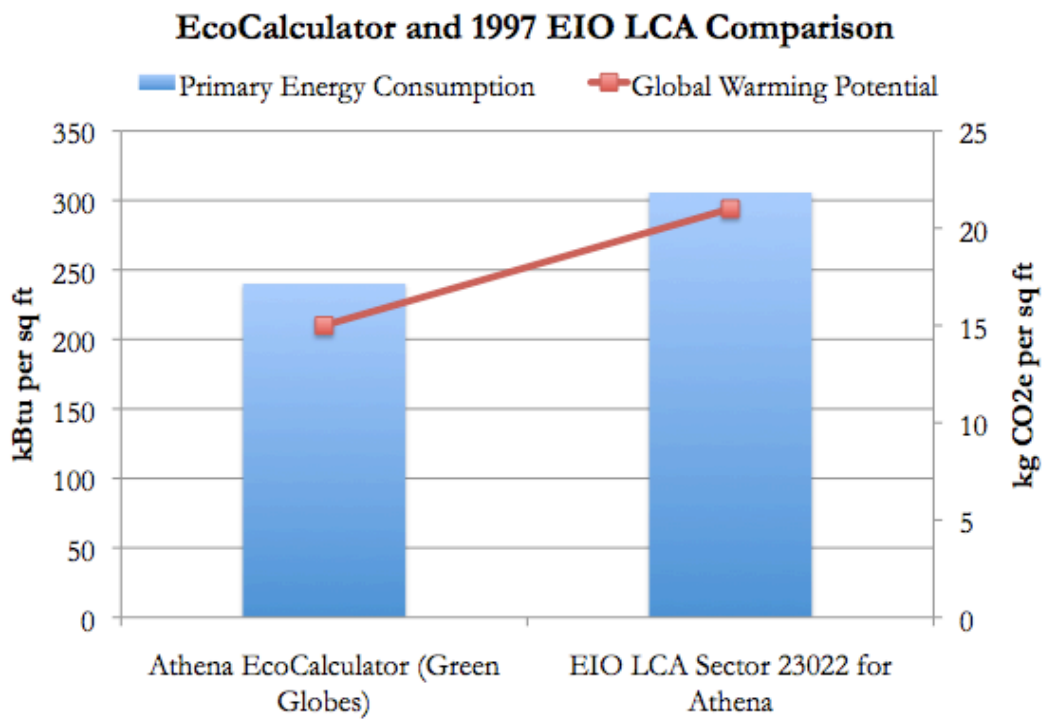

Table 4-22. Energy and carbon comparison of Athena EcoCalculator to EIO LCA.

4.4 Hybrid LCA model for building environmental assessment

The ideal LCA in a building environmental assessment method would account for all environmental effect and reveal all the ways designers and other stakeholders can reduce that impact. This section will present a hybrid model that achieves these objectives by combining the EIO LCA and process-based LCA approaches.

4.4.1 Previous hybrid models

Several hybrid EIO LCA and process-based LCA models have been developed to evaluate the construction of different types of infrastructure (Bilec et al 2006). However, none of them lend themselves to quick analyses that could be implemented during the building design process.

4.4.2 EcoCalculator-EIO-LCA hybrid model

The EcoCalculator-EIO-LCA hybrid model proposed in this section combines the best aspects of the EcoCalculator and the 1997 EIO LCA national average data. The EcoCalculator can be used early on in commercial building design to inform selection of building assemblies, while the 1997 EIO LCA national averages covers a much larger boundary of analysis and thus more accurately estimates the total environmental effect. This hybrid model, which can only be used for commercial buildings, is based on the result from section 4.3.3.3 that, after reducing the EIO LCA boundary of analysis to that of the Athena EcoCalculator, the energy consumption and carbon emissions per square foot of commercial building construction is only 21% and 20% of the total, respectively.

There are two basic inputs to the model. The first is an estimate of a building's percent reduction carbon emissions from the average. This estimate should be developed using the Athena EcoCalculator and the Green Globes approach. As described in Section 3.2.2, this approach includes an iterative process of selecting alternative building assemblies that have above- or below-average embodied carbon emissions. As an example, a final estimate was made for one building and the results are shown in Table 4-23.

	Carbon emissions
	t CO2e
Estimate based on "average" assemblies	230
Estimate based on design	170
Percent reduction	25%

Table 4-23. Results from an analysis of an arbitrary building using EcoCalculator.

The second input is a total EIO LCA carbon emissions estimate. This estimate should be developed using the value in Table 4-7 for a commercial building: 120 kg CO_2e per square foot. Since the percent reduction calculated in Table 4-13 was calculated using the Athena EcoCalculator, it should be applied only to the EcoCalculator boundary of analysis, which is 20% of the total EIO

LCA. Thus, the carbon emissions reduction is only 5% of the total EIO LCA figure. The results of this Hybrid LCA approach are shown in Figure 4-15.

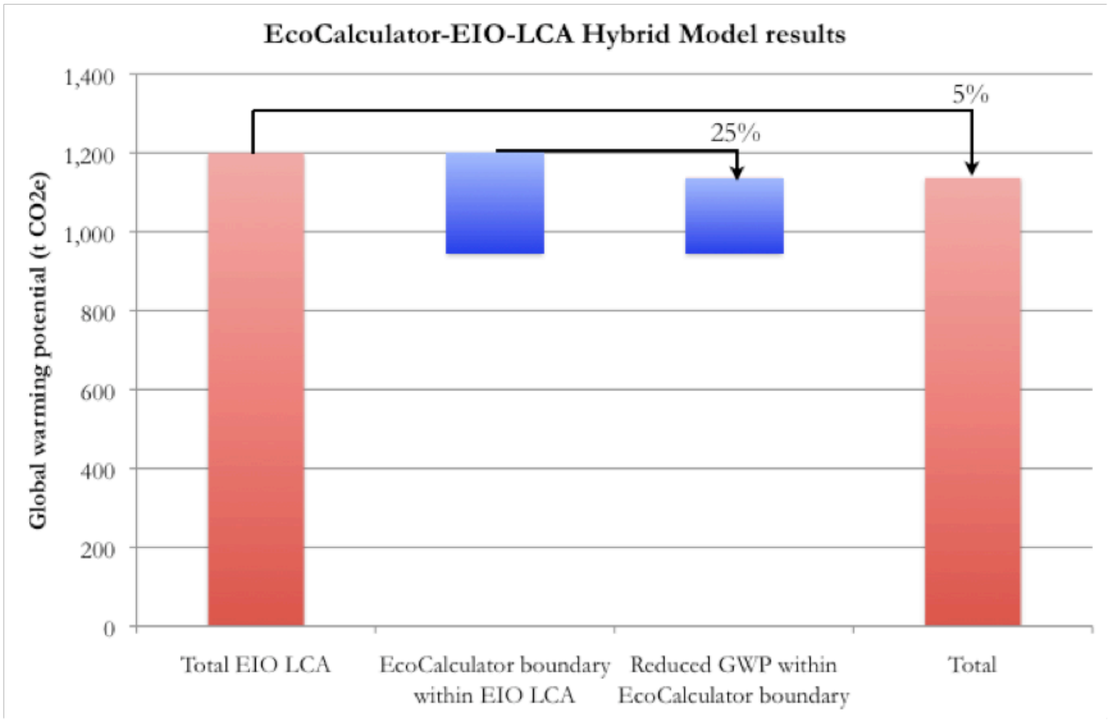

Figure 4-7. Results from the EcoCalculator-EIO-LCA Hybrid Model. After determining a 25% reduction with the EcoCalculator, a more comprehensive carbon emissions estimate was made using EIO LCA. Since the EcoCalculator covers only a portion of the EIO LCA boundary of analysis, the total carbon emissions reduction is only 5%.

4.5 Discussion and conclusions

This chapter presented national averages for the embodied carbon emissions per square foot of commercial, industrial, and residential buildings. The chapter also presented a hybrid model that combines the best aspects of the EcoCalculator and 1997 EIO LCA data. As discussed above, the EIO LCA estimates are only meant to provide a general sense of environmental effect and are not meant to be very precise.

Since the EcoCalculator is already being used by Green Globes, it seems likely that Green Globes or another building environmental assessment method could also adopt the hybrid model proposed here. Why would developers of such assessment methods want to adopt such a hybrid model?

It is clear from this chapter that a process-based LCA approach such as the one provided by the EcoCalculator grossly underestimates the actual environmental effect of building projects. The carbon emissions estimate provided by the hybrid model is about five times the size of the EcoCalculator estimate. Such a very large discrepancy warrants careful consideration as to how well the EcoCalculator leads designers to actually making the optimal design decisions. For example, if the carbon emissions from the construction phase of a building project are only a very small fraction of the emissions for the entire building lifecycle, why give it any consideration at all? Indeed, helping designers answer such questions with good data is the intent of the following chapter.

Chapter 5: Making a carbon model of building projects

The previous chapters have described a need for building environmental assessments to incorporate carrying capacity, to better influence the design process, and to more comprehensively take into account the carbon emissions associated with the construction of buildings. This chapter proposes a carbon model that could be used by building environmental assessment systems to achieve these objectives.

The carbon model estimates net carbon flow from the earth to the atmosphere, or vice versa, as a result of a building project—from its inception through its expected operational lifetime. While an energy model produces an estimate of energy consumption and compares this to other buildings, a carbon model views this energy consumption as carbon emissions and shows how far away a project is from its allotted carrying capacity.

Carrying capacity is defined in this model as the amount of carbon stored on the building project site in its native state. The best-case building in this model is one that contributes a net *positive* carbon flow from the atmosphere to the earth within the expected life of the building. There is no theoretical limit to the magnitude of this flow.

This chapter is organized into three sections. The first section provides a more detailed description of the carbon model. The second section describes how the model is built and reports its application in an institutional building project in Lake Placid, Florida. The third section presents results from the case study and a discussion.

5.1 Introduction to the carbon model

5.1.1 Overview of the carbon model

If we think back to a time when there were no buildings, the amount of carbon stored in the native vegetation and soil on the buildings sites helped to maintain a global carbon balance between the earth and atmosphere. Thus, the carbon model uses the native amount of stored carbon as a benchmark for building assessment, or the carrying capacity of the building project. Any vegetation that is removed from the site or any carbon emissions that are emitted from the site (such as to operate a building) can be thought of as an ecological mortgage that needs to be repaid, otherwise there will be an anthropogenic increase in atmospheric carbon.

The carbon model can be summed up by one equation, as follows:

$$CS\,(t) = NSCS - SD - C - O\,(t)$$

Equation 1. Carbon model.

Where:
CS = Carbon storage on the building site (kg CO_2e)
t = Time (years)
NSCS = Native-site carbon storage (kg CO_2e)
SD = Emissions from site development (kg CO_2e)
C = Emissions from building construction (kg CO_2e)
O = Emissions from building operation (kg CO_2e/year)

As shown in Figure 5-7, the emissions from site development and building construction occur during only the first year of the building project. Figure 5-7 also illustrates three separate scenarios for the operation phase of the building. The scenario represented by the red line shows how the building continues to emit carbon and goes into greater carbon debt. The orange line represents a net zero operational carbon emissions scenario and the blue line represents a building that has negative operational carbon emissions. The dips in the lines represent possible retrofits that would each carry an amount of embodied carbon emissions (at this point, these dips are not quantified nor are they included in above equation).

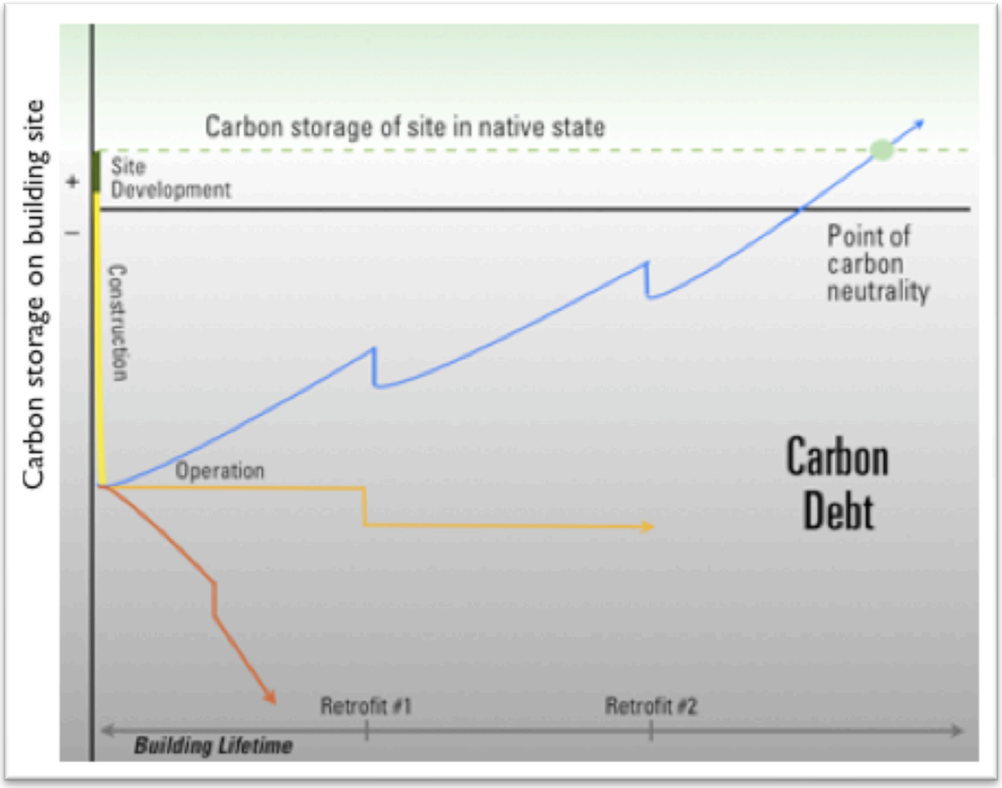

Figure 5-8. Carbon model. The carbon stored on the building site (y-axis) goes up or down with the threes aspect of the building project: site development, construction, and operation. If during the operation phase a building can reach back up to the amount of carbon stored on the site in the native state, the building project is considered "carbon neutral."

As shown in Figure 5-8, the carbon model shows whether or not the building project is contributing to a net increase or decrease in atmospheric concentration of greenhouse gasses.

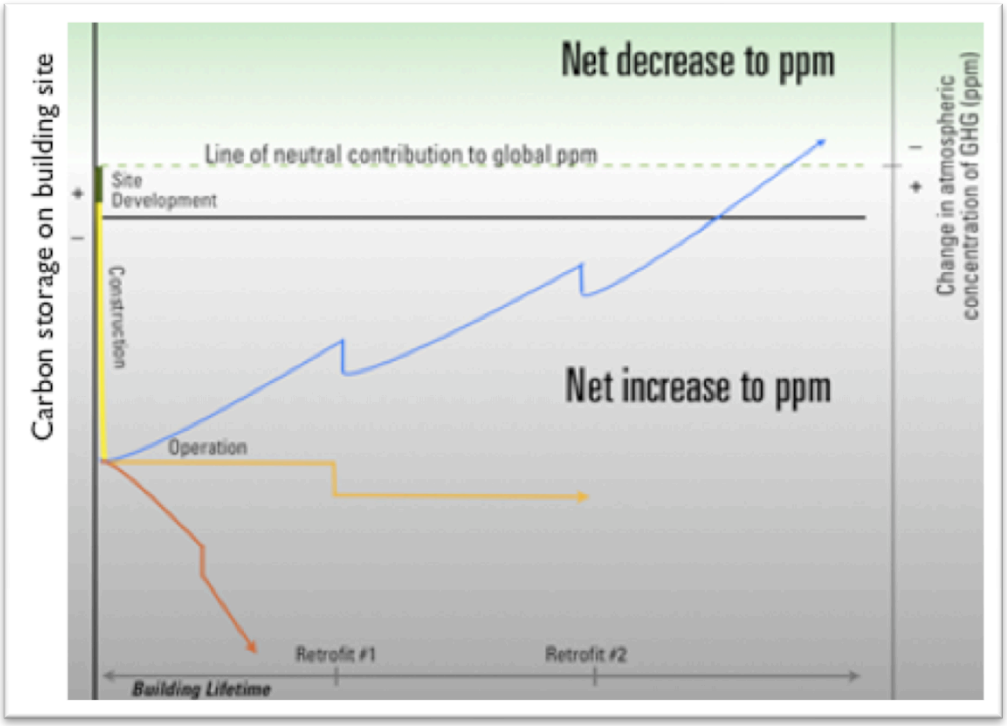

Figure 5-9. Carbon model can show a net increase or decrease to parts-per-million (ppm) of carbon in the atmosphere. If the carbon storage on the building site increases to a point above the native site carbon storage, or the "line of neutral contribution to global ppm," the project will result in a net decrease in concentration of greenhouse gasses.

5.1.2 Establishing the native site carbon storage

The first step to creating a carbon model is to establish the carrying capacity, or the native-state carbon storage on the building site. The IPCC has gathered several studies of carbon storage specific to land types including forests and grassland, as shown in Table 5-1. New studies continued to be conducted (Powell et al 2006, Alexis et al 2006); unfortunately, there is no available data for land types other than forest or grassland.[1] In addition, the studies do not account for underground biomass, which can be as high as 80 percent of the total biomass (Swain 2008).

[1] Marsh land, for instance, is drained and built on frequently in the US

ABOVE-GROUND BIOMASS IN FORESTS

Domain	Ecological zone	Continent	Above-ground biomass (tonnes d.m. ha^{-1})
Temperate	Temperate oceanic forest	Europe	120
		North America	660 (80-1200)
		New Zealand	360 (210-430)
		South America	180 (90-310)
	Temperate continental forest	Asia, Europe (≤20 y)	20
		Asia, Europe (>20 y)	120 (20-320)
		North and South America (≤20 y)	60 (10-130)
		North and South America (>20 y)	130 (50-200)
	Temperate mountain systems	Asia, Europe (≤20 y)	100 (20-180)
		Asia, Europe (>20 y)	130 (20-600)
		North and South America (≤20 y)	50 (20-110)
		North and South America (>20 y)	130 (40-280)

Table 5-24. Biomass of various ecological zones. The IPCC recommends multiplying the biomass by a carbon fraction of 0.5 to obtain the carbon (C) content, which will then have to be multiplied by a factor 44/12 to obtain CO_2 mass. See Appendix D for the complete list of stored carbon values for different land types from the IPCC.

$$NSCS = CI \times SA$$

Equation 2. Native site carbon storage.

Where
NSCS = native site carbon storage (kg CO_2e)
CI = Carbon intensity of the native ecological zone (kg CO_2e/sq ft)
SA = Site area (sq ft)

5.1.3 Estimating carbon emissions from site development

Site development is perhaps most well known as forest depletion. For instance, forests in Africa are becoming smaller due to increased consumption of wood for cooking. Also, rain forests in South America are being converted to farmland that stores much less carbon. Using the same method developed by the IPCC to account for this depletion in carbon storage and resultant carbon emissions, it is possible to calculate the emissions associated with land or site development for buildings and urbanization (IPCC 2006).

The emissions from site development should be calculated by comparing the design case carbon storage with the native-state carbon storage, as shown in Equation 3. The design case carbon storage may include some percentage of the site that has native vegetation, in which case that percentage should be multiplied with the native-state carbon storage. On areas with no native vegetation the number of trees can be estimated and converted to stored carbon, using Table 5-25.

$$SD = NSCS - (\%Native \times NSCS) - (Trees \times CR \times Yrs)$$

Equation 3. Emissions from site development.

Where:
SD = Emissions from site development (kg CO_2e)
NSCS = Native site carbon storage (kg CO_2e)
%Native = Percent of building site that will have native vegetation in its design state
Trees = Number of trees expected on the site in non-native areas
CR = Rate at which the trees sequester carbon during growth period (kg CO_2e/yr)
Yrs = Length of trees growth period (yr)

Species	Default annual carbon accumulation per unit (t C/yr)	Growing period (yr)	Number of trees on site	Carbon sequestered (kg C/yr)
Aspen	0.0096	20	0	0
Soft maple	0.0118	20	0	0
Mixed hardwood	0.01	30	0	0
Hardwood maple	0.0142	20	0	0
Juniper	0.0033	20	0	0
Cedar/larch	0.0072	20	0	0
Douglas fir	0.0122	20	0	0
Pine	0.0087	20	0	0
Spruce	0.0092	20	0	0
Total				0
Source:	2006 IPCC Guidelines for National Greenhouse Gas InventoriesVolume 4: Agriculture, Forestry and Other Land Use, Table 8.2			

Table 5-25. The amount of carbon sequestered on site by individual trees is estimated using this table developed from the IPCC Guidelines.

5.1.4 Estimating emissions from building construction

The emissions from the building construction include all site work (earth moving, assembling, etc.) and the embodied carbon emissions of materials (from the extraction of raw materials through transportation to site). As discussed in chapters 3 and 4, these emissions can be estimated using both process-based and economic input-output LCA. This thesis recommends using the EcoCalculator-EIO-LCA hybrid model described in chapter 4 and further defined in Equation 4.

$$C = (1 - \%reduction \times 20\%) \times EIOLCA$$

Equation 4. Emissions from building construction

Where:

C	=	Emissions from building construction (kg CO_2e)
%reduction	=	The percent reduction in carbon as calculated using the Athena EcoCalculator
EIOLCA	=	The total carbon emissions from building construction based on the 1997 EIO LCA carbon intensity values presented in Table 4-16 (kg CO_2e)

5.1.5 Estimating emissions from building operation

During the operation of the building, the flow of carbon can move either into or out of the atmosphere. In order to determine the direction and magnitude of this flow, assumptions need to be made regarding the emissions intensity of the energy sources. The calculation of energy emissions can be described as two steps.

The first step is to estimate how much and what mix (electricity, natural gas, etc.) of energy the building will use. It is straightforward to calculate the emissions of this mix of energy with emissions factors from the U.S. Environmental Protection Agency and Energy Information Administration.

The second step is to estimate the emissions offset. In almost all cases, the amount of carbon offset by purchasing RECs or other carbon offsets is explicit (e.g., Native Wind[2] sells RECs at \$12/ton CO_2). The carbon offset by on-site renewable energy is also straightforward. The carbon intensity (kg CO2e/kBtu) of on-site electricity should equal that of purchased electricity. The carbon intensity of energy produced by a solar thermal system should equal that of whatever the auxiliary energy source is – for instance, in most cases, natural gas.

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[2] www.nativewind.org

$$O(t) = (E - EG)EI + (NG - RE)NGI + (OF - RE)OFI$$

Where:

O	=	Carbon emissions from building operation (kg CO_2e)
E	=	Electricity used (kBtu)
EG	=	Electricity generated on-site (kBtu)
EI	=	Electricity carbon emissions intensity (kg CO_2e/kBtu)
NG	=	Natural gas used (kBtu)
RE	=	Renewable thermal energy from on-site (kBtu)
NGI	=	Natural gas carbon emissions intensity (kg CO_2e/kBtu)
OF	=	Other fuel used (kBtu)
OFI	=	Other fuel carbon emissions intensity (kg CO_2e/kBtu)

5.2 Making and applying a carbon model: a case study

5.2.1 Introduction

Working for Rocky Mountain Institute (RMI), the author of this thesis built a carbon model for a building project in central Florida. The client, Archbold Biological Station (Archbold), is a non-profit independent research institution that conducts research, engages in preservation, and educates the local community and beyond. Having grown out of its current facilities, Archbold is about to design a new Lodge and Learning Center (LLC). RMI was asked to conduct a pre-design charrette to aid in this process. The carbon model was presented at this pre-design charrette on November 5, 2008. The model was used for goal-setting purposes. In addition, building stakeholders later adopted the model as an indicator of building sustainability: the design team is planning an interactive display that tracks building performance couched in the carbon model.

5.2.2 Establishing carrying capacity

The site of the LLC is on the northern edge of Archbold campus, near Lake Placid, Florida. It has been defined as 1.39 hectares. The pre-development state of the site was an ecosystem known as scrub oak. A biological research institution, Archbold provided carbon storage studies of the local ecosystem. The stored carbon in the native vegetation ebbs and flows with each natural burn and produces a small amount of charcoal that eventually disintegrates (Alexis et al 2006). Assuming that the natural burn cycle is about 17 years (Swain 2008), the average carbon stored is 5.5 kg C/m^2 (55 mt C/ha). Similar to the IPCC estimates, this estimate does not include underground biomass. In the case of Florida scrub oak, the underground biomass accounts for more than 80 percent of the total (Swain 2008). Therefore 5.5 kg C/m^2 is a major underestimate.

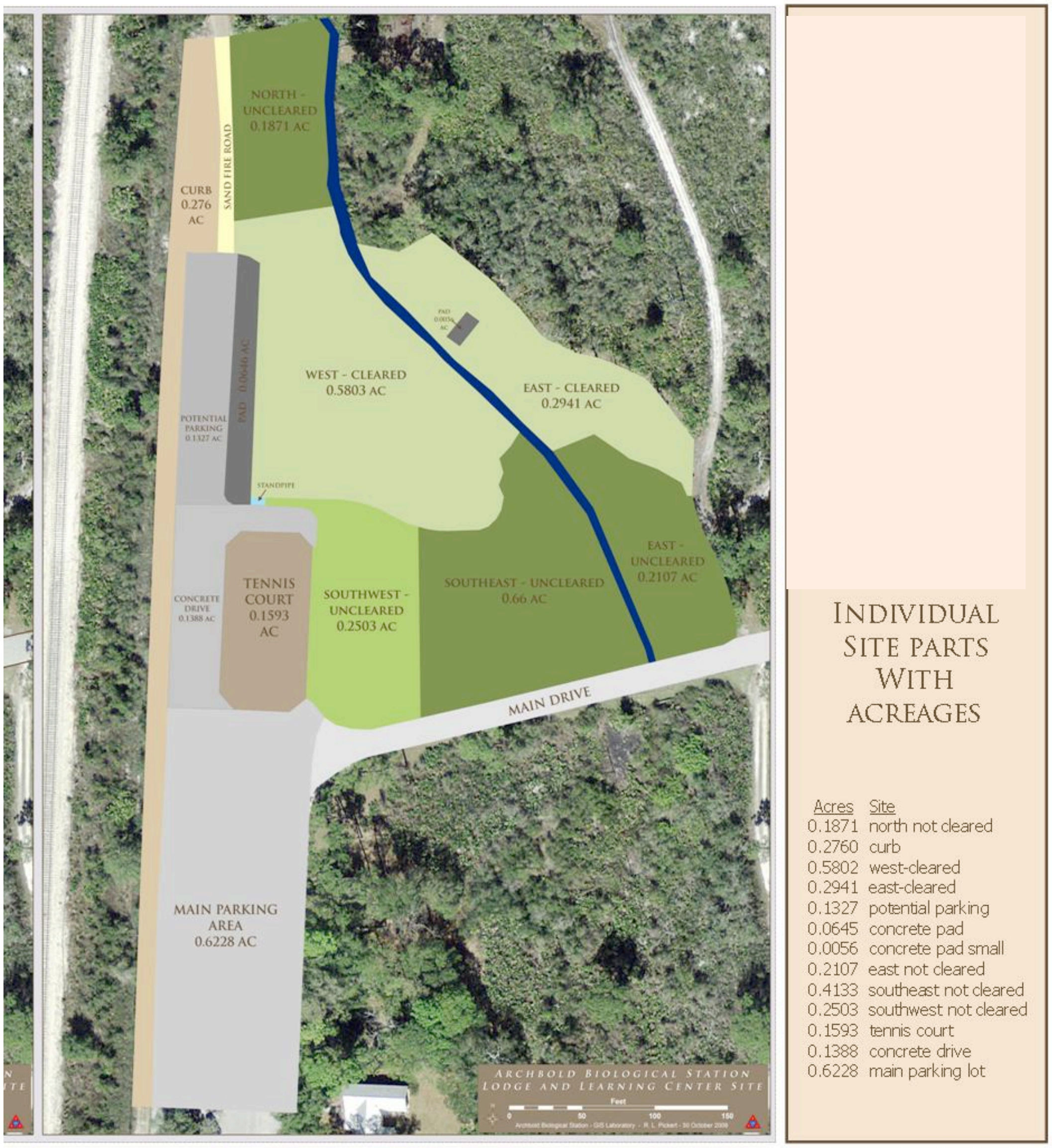


Figure 5-10. The site of the LLC is in the midst of scrub oak. Much of the scrub has already been cleared to make way for construction.

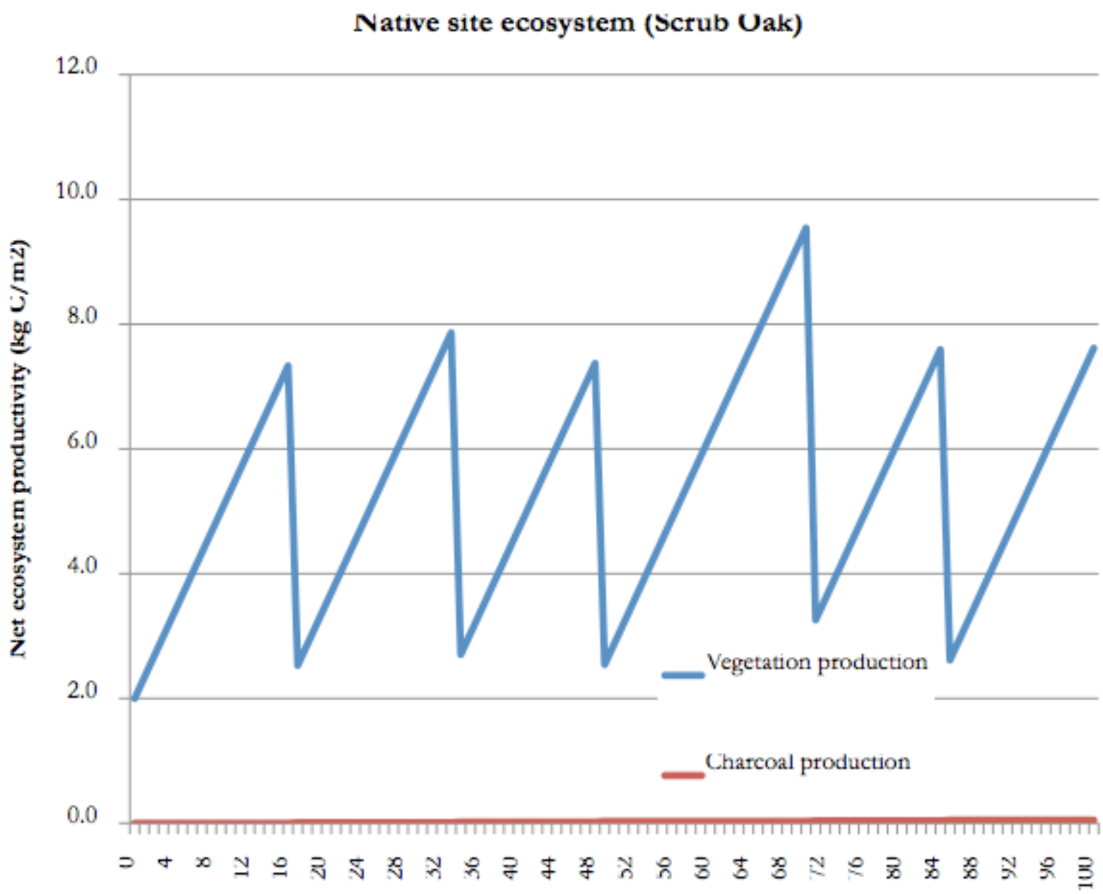


Figure 5-11. Graphic illustration of native site carbon storage (labeled "net ecosystem productivity") with average 17-year burn cycle, including some variation, over the course of 100 years. The average carbon stored is 5.5 kg C/m^2.

5.2.3 Emissions from site development

Over 50% of the site is to be returned to native ecosystems. The 1.39 ha design site was modeled at

- 7830 m^2 scrub oak;
- 5110 m^2 nonporous surface; and
- 994 m^2 building footprint.

As the design moves forward, these estimates can be adjusted. If non-porous surfaces are replaced with vegetation, the total carbon stored on-site will increase.

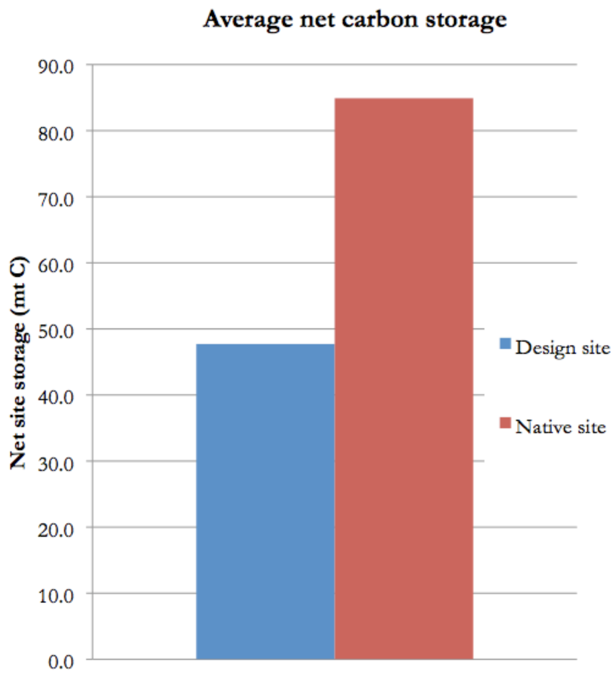


Figure 5-12. Amount of carbon stored on the 1.39 ha site.

The amount of carbon stored on-site can also be increased through the planting of individual trees. According to Table 5-25, ten pines trees over the course of a 20-year growing period (after which growth is negligible) would store 1.7 mt C, or about 4% of the design site stored carbon. Care was taken to not double count areas of forestland and individual tress.

5.2.4 Emissions from building construction

The LLC will be a 10,500 ft^2 building that is categorized in the EIO LCA sector Commercial and Institutional Buildings. The embodied carbon was estimated based on the EIO LCA estimate presented in chapter 4. The client requested that all CO_2e figures are converted to carbon (C) and those results are presented here.[1]

Embodied Energy of the LLC			
Building type	National average carbon intensity (kg C/ft^2)	Area of building (ft^2)	Total Carbon emissions (metric tons C)
Commercial and Institutional	32	10,500	310

Table 5-26. This initial estimate of the LLC can be refined later using the hybrid model described in chapter 4.

5.2.5 Emissions from building operation

Energy Star's Target Finder tool was used to provide an initial estimate of energy use by the building (which had not yet been energy modeled).[2] Separate estimates were made for the Lodge and the Learning Center. The energy results were then translated to an estimate of carbon emissions using the local electricity fuel mix and a source to site ratio of 1.047 for natural gas.[3] A 60% reduction case was also calculated for presentation purposes (this goal would meet the Architecture 2030 Challenge).

Table 5-28 shows the emissions factors that were used for this project.

Emissions factors in Florida		
	Electricity	Natural gas
kg C/kBtu	0.054	0.015

Table 5-27. Emissions factors for electricity and natural gas. Source: EPA eGrid and DOE EIA.

[1] Since there are two parts oxygen (molecular weight of 16) and one part carbon (molecular weight of 12) for every unit mass of carbon dioxide, a factor of 12/44 converts a mass of CO_2 to C.

[2] Target Finder is based on the Department of Energy Commercial Building Energy Consumption Surveys (CBECS).

[3] The electricity emissions factors, which include transmission and distribution losses, can be found on the EIA Voluntary Reporting of GHG Emissions website: http://www.eia.doe.gov/oiaf/1605/techassist.html. The site to source ratio comes from the EPA's Energy Star program: http://www.energystar.gov/ia/business/evaluate_performance/site_source.pdf.

According to Target Finder, the mix of energy coming to the site is 30% natural gas and 70% electricity. The carbon emissions per Btu from this mix of energy is calculated by taking a weighted average of the emissions intensities of each fuel. this indicates that the offset rate from electricity generated on-site will be larger than the rate at which carbon is emitted by the energy coming on-site. Table 5-32 shows the difference in carbon intensity of energy coming to the site versus the rate at which carbon is offset with electricity generated on-site.

Comparison of carbon intensity		
	Energy from off-site (30% natural gas and 70% electricity)	On-site renewable electricity
kg C/kBtu	0.042 (emissions)	0.054 (offset emissions)

Table 5-28. Comparison of carbon intensity of energy coming to the site and generated on-site.

Table 5-33 provides more details about the anticipated energy use and resultant carbon emissions for the Lodge and Learning center.

		Average building		60% Reduction	
		Lodge (kBtu/yr)	Learning (kBtu/yr)	Lodge (kBtu/yr)	Learning (kBtu/yr)
Energy	Energy Use Intensity (kBtu/sq ft-yr)	87.0	45.6	35.8	20.4
	Average EUI (kBtu/sq ft-yr)	65.3		27.8	
Carbon	Carbon intensity (kg C/sq ft-yr)	3.32	2.18	1.37	0.98
	Average Carbon intensity (kg C/sq ft-yr)	2.73		1.16	

Table 5-29. Carbon and site energy intensity values. “Average building” energy use intensity values are from Target Finder.

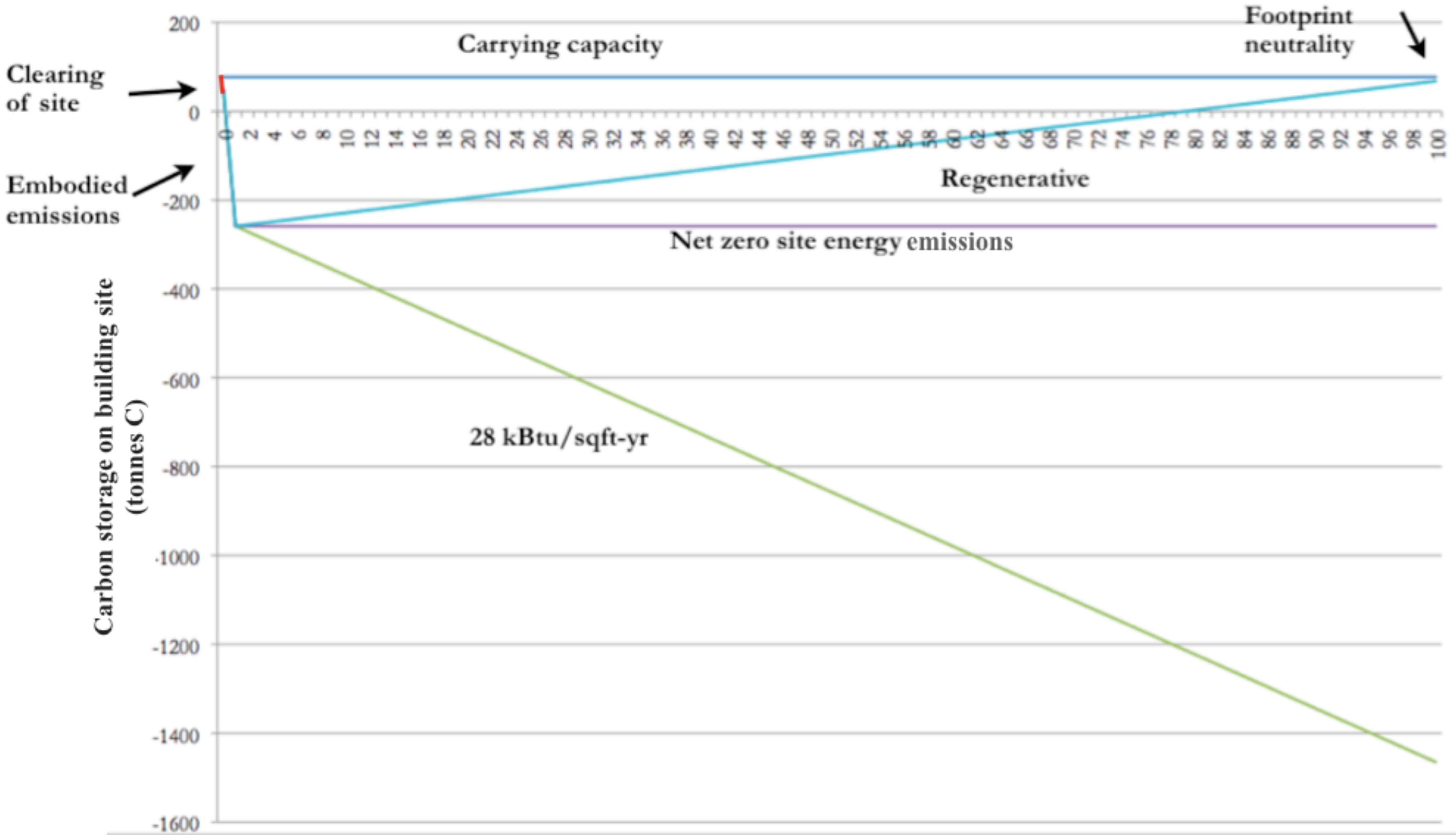
5.3 Results and discussion

5.3.1 A long-term and comprehensive forecast

The model produces a long-term and comprehensive forecast of carbon flow for alternative building project scenarios. For the Archbold charrette, three different scenarios were input to the model and are depicted in Figure 5-34. The scenarios only differ during the building operation phase. The first is a 60 percent reduction in operation emissions relative to the Target Finder estimate. This scenario, named "28 kBtu/sq ft-yr" on the chart, assumes the LLC will use 28 kBtu (site energy) per square feet per year. While this energy performance is very good, it nonetheless drives the buildings into greater carbon debt. Other scenarios are "net zero site energy emissions" in which the balance between annual carbon emissions from off-site and on-site energy is zero, and a final scenario named "regenerative" that reaches back up to the line of native-state carbon storage, labeled "carrying capacity."

In addition to showing alternative building operation emissions scenarios, the long term and comprehensive forecast by the carbon model makes it easy to understand the operation emissions relative to clearing the vegetation from the site and the emissions from construction.

Figure 5-13. Carbon emissions over building lifetime. Alternative scenarios during building operation are also plotted.



5.3.2 Influence on design process

The carbon model presented at the charrette for Archbold was successful at bringing about a shared understanding among stakeholders. Everyone could understand how the "regenerative" building line, as represented on the chart, needed to reach back up to the native amount of stored carbon (Swain 2008). This influenced the design team to incorporate the carbon model into an interactive display that tracks building performance. The long-term carbon goal was simple enough to bring about shared understanding, yet, at the same time, powerful enough to motivate stakeholders toward an ambitious design goal.

Stakeholders felt that the power to stay within the limits defined by the carbon model was in their hands. They were able to take ownership of the environmental effect of the building project. In this way, a global problem such as climate change became more localized and more manageable. Rather than relying on some geo-engineering strategy to solve the problem on the global scale, stakeholders could envision how the problem can be addressed on a more personal level, building by building.

In addition to its shared understanding and motivational effects, the carbon model has an influence on the design approach. Charrette participants were confronted with an ecologically based limit on their building. The building could not be any kind of building but needed to be something within the limits defined by the carbon model. These limits are different from the more typical constraints of time and cost in that they are more linked to the natural processes of the earth (of which many designers are uninterested). So the motivational effect directs one toward a goal defined by the natural world. In this way, the carbon model brings greater awareness and interest of design strategies that are reactive to the natural world. Thus, just as carrying capacity provides orientation as noted in Section 2.1, this carbon model encourages designers toward a more climate-sensitive, bio-climatic approach.[1]

5.3.3 Feasibility of footprint neutral

Footprint neutrality is not an easy goal, but it is within reach. A pre-feasibility study was made for the LLC project regarding footprint neutrality. The following table shows the size of the on-site, grid-connected solar array required to meet possible goals of net zero site energy emissions and footprint neutrality if the LLC requires an average 28 kBtu per square feet per year. Since 28 kBtu per square foot equals at total of 12 tonnes C per year (or 1.16 kg C/ft^2-yr), this same amount needs to be offset in order to reach net zero site energy emissions. In order to reach footprint neutrality, the offset rate needs to be an additional 4 tonnes C, for a total of 16 tonnes C, per year in order to offset the carbon emissions of construction and the clearing of site vegetation.

Panel	Panel efficiency	Capacity (kW)	Array area (ft^2)	Production (MWh/yr)	Goal
Sharp mono-si-NT-175U1	13.4	66	5300	86	Net zero site energy emissions
		85	8500	110	Footprint neutrality

Table 5-30. Options for solar PV related to goals. Source for PV panel characteristics: RETScreen.

[1] The design approach hereto referred is described in *Design With Climate* (Olgyay 1963).

Chapter 6: Toward an assessment of building sustainability: summary and recommendations

Despite a growing concern for global warming and heightened interest in emissions cuts, the concept of carrying capacity has remained unheard of in building environmental assessment methods of today. All methods are positioned to bring about high performance buildings, but none use carrying capacity as a benchmark. In academia, carrying capacity has been mentioned as an ideal toward which methods should develop (Cole 1999), yet only one method to incorporate carrying capacity has been proposed (Olgyay and Herdt 2004). This thesis contributes to what will ideally become a more active discussion regarding the intersection of building assessment, carrying capacity, and sustainability. This concluding chapter reports provides summaries of the contribution of this thesis and provides recommendations for building assessment methods, government policy, and future research.

6.1 Summary and discussion of embodied emissions assessment

Key contributions of this thesis include a critical discussion of existing LCA methods and the presentation of a new LCA model for building construction. The critical discussion produced three major conclusions. One is that EIO LCA has a much larger boundary of analysis than process-based LCA and accounts for nearly all carbon emissions that can be attributed to a building. Another is that the Athena Institute's EcoCalculator, while covering a much smaller boundary of analysis, informs design decisions much better than EIO LCA can. Finally, the two methods compliment each other well and a hybrid model could capture the benefits of both.

The EIO LCA method and Athena EcoCalculator were combined to form a hybrid LCA model. The EIO LCA method relies on data from a research team at Carnegie Mellon University that developed a public-access, online calculator. Data from this calculator and other sources was used to make a US-specific EIO LCA of building construction on a square foot basis. After some manipulation of data, this method was combined with the Athena Institute's EcoCalculator. A hybrid model was produced, which allows users to benefit from the comprehensiveness of the EIO LCA approach while still having the ability to get useful design information upfront from the Athena EcoCalculator.

6.2 Summary and discussion of carbon model

The carbon model presented in this thesis compares the amount of carbon that would be stored on building site in its native state to the carbon emissions that occur over the building's lifetime. The model accounts for the carbon emissions from developing the site, the carbon emissions from the construction of the buildings, and the building operational emissions. By using this model, designers are better able to understand how the building project is contributing to the flow of carbon from the earth to atmosphere. In addition, they are better aware of sources of carbon emissions that are commonly not considered: site development and construction emissions.

The emissions from site development is important to take into account because it reveals the opportunity to sequester a substantial amount of carbon in the US through the judicious planting of trees and other vegetation in and around buildings. A recent US Geological Survey report indicates that it would be appropriate for urban and other areas to store 3–7 gigatonnes (Gt) more carbon (Sundquist et al., 2009), which would reduce 5–12 ppm of CO_2e in the atmosphere.[2]

[2] The decrease in ppm as a result of increase in net carbon storage can be calculated as follows. The mass of Earth's atmosphere is about 5.15E18 kg. Divide this by the mean molar mass of atmospheric molecules, 0.02884 kg/mole, to obtain 1.785E20 moles. One gigatonne of carbon corresponds to: 1E12 kg divided by 0.012 kg/mole, which equals 8.33E13 moles. And, 8.33E13 divided by 1.785E20 is about 4.7E-7, or 0.47ppm of C. Multiply 0.47 by 44/12 to obtain ppm of CO_2 per gigatonne C. (Flanner 2009)

The carbon emissions from building construction represents 8 percent of the total US carbon emissions, according to Architecture 2030, a non-profit think tank. While this thesis has shown that quantifying these emissions for a particular building project is challenging, it is nonetheless important to be aware of this emissions source and take action to reduce it.

6.3 Recommendations

6.3.1 Recommendations for Green Globes and LEED

The two major building assessment methods in the US, Green Globes and LEED, can benefit from the work of this thesis. The hybrid EcoCalculator-EIO-LCA model provided here can be used to determine carbon emissions from the manufacturing of materials to the end of building life. In addition, the carbon model can be employed to create a baseline of carrying capacity.

Currently, Green Globes uses the Athena EcoCalculator to assess carbon emissions from building construction and LEED does not quantify carbon emissions at all. Thus, the quantified carbon emissions from building construction are grossly underestimated by these methods. Both methods should adopt the hybrid EcoCalculator-EIO-LCA model to enable users to better understand the magnitude of the carbon emissions resultant from building construction.

Neither Green Globes nor LEED enables users to take a comprehensive view of the carbon emissions from the building project. The carbon model would provide a unique feature to the assessment methods and would take the methods closer to an absolute form of measure that has long been sought after in the field of building environmental assessment.

6.3.2 Policy recommendations

A major limitation in the LCA models proposed in this thesis is the lack of specificity for different building types. The US Census Bureau can, but does not, gather data on the subsectors of commercial and institutional buildings. This data gathering would enable estimates like the ones provided in CASBEE, where several different space types are provided – as opposed to the single commercial and institutional buildings sector.

6.4.3 Future research

Future research should be directed toward achieving two objectives: (1) identifying all sources carbon emissions and accurately calculating them for a given building project and (2) identifying ways to reduce those carbon emissions and accounting for reductions. This thesis has provided a carbon model that accomplishes these two objectives to a certain extent, but there are several areas of improvement. For instance, this thesis relies on national averages to estimate the carbon emissions from constructing a particular building. It would be better to use a method that produces results only valid for a particular building.

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Appendix A: Bureau of Economic Analysis IO Total Requirements Table Calculation Procedure[3]

December 10, 2002

Mathematical Derivation of the Total Requirements Tables for Input-Output Analysis[4]

From make and use tables, the following are defined:

q: Total commodity output. It is a commodity-by-one vector.

g: A column sector in which each entry shows the total amount of each industry's output, including its production of scrap. It is an industry-by-one vector.

U: Intermediate portion of the use matrix in which the column shows for a given industry the amount of each commodity it uses, including noncomparable imports and scrap, used and secondhand goods. This is a commodity-by-industry matrix.

V: Make matrix, in which the column shows for a given commodity the amount produced in each industry. It is an industry-by-commodity matrix. V has columns showing only zero entries for noncomparable imports and for scrap.

^: A symbol that, when placed over a vector, indicates a square matrix in which the elements of the vector appear on the main diagonal and zeros elsewhere.

B: Direct input coefficients matrix in which entries in each column show the amount of a commodity used by an industry per dollar of output of that industry. It is a commodity-by-industry matrix.

$$B = U\hat{g}^{-1} \qquad (1)$$

D: A matrix in which entries in each column show, for a given commodity (excluding scrap), the proportion of the total output of that commodity produced in each industry. It is assumed that each commodity (other than scrap) is produced by the various industries in fixed proportions (*industry technology assumption*). D is an industry-by-commodity matrix. D is also referred to as the market share matrix or transformation matrix.

$$D = V\hat{q}^{-1} \qquad (2)$$

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[3] Prepared by the BEA

[4] The notation and derivation of the tables presented follow the System of National Accounts recommended by the United Nations. See: A System of National Accounts Studies in Methods, Series F No. 2 Rev. 3, United Nations, New York, 1968; also, Stone, R., Bacharach, M. & Bates, J., "Input-Output Relationships, 1951-1966," Programme for Growth, Volume 3, London, Chapman and Hall, 1963.

i: Unit (summation) vector containing only l's.

I: Identity matrix, where I = $\hat{i}$.

e: A column vector in which each entry shows the total final demand purchases for each commodity from the use table.

h: A column vector in which each entry shows the total amount of each industry's production of scrap. Scrap is separated to prevent its use as an input from generating output in the industries in which it originates.

p: A column vector in which each entry shows the ratio of the value of scrap produced in each industry to the industry's total output.

W: An industry-by-commodity matrix in which the entries in each column show, for a given commodity, the proportion of the total output of that commodity produced in each industry adjusted for scrap produced by the industry.

From the above definitions, the following identities are derived:

$$q = Ui + e \qquad (3)$$

$$g = Vi + h \qquad (4)$$

Scrap output in each industry is proportional to total output of the industry, then:

$$h = \hat{p}g \qquad (5)$$

The model expressed in equations (1) through (5) thus involves three constants (*B, D, p*) and six variables (*U, V, h, e, q, g*). The model solution is derived as follows:

From (1) and (3), we derive:

$$q = Bg + e \qquad (6)$$

From (2) and (4), we derive:

$$g - h = Dq \qquad (7)$$

Substituting (5) into (7) and solving for g:

$$g - \hat{p}g = Dq$$
$$(I - \hat{p})g = Dq$$

$$g = (I - \hat{p})^{-1} Dq \qquad (8)$$

Let $(I-\hat{p})^{-1}D = W$, then

$$g = Wq \qquad (9)$$

Substituting (9) into (6) and solving for q:

$$q = BWq + e$$

$$(I - BW)q = e$$

$$q = (I - BW)^{-1} e \qquad (10)$$

Substituting (10) into (9) gives:

$$g = W(I - BW)^{-1} e \qquad (11)$$

Therefore, three total requirements coefficients matrices are derived[5]:

Commodity-by-commodity total requirements matrix:

$$(I - BW)^{-1} \qquad (12)$$

which shows commodity output required per dollar of each commodity delivered to final users.

Industry-by-commodity total requirements matrix:

$$W(I - BW)^{-1} \qquad (13)$$

which shows the industry output required per dollar of each commodity delivered to final users.

And the industry-by-industry total requirements matrix:

$$(I - WB)^{-1} \qquad (14)$$

which shows the industry output required per dollar of each industry product delivered to final users.

[5] Tables are prepared at the detailed, summary and sector levels of aggregation.

Appendix B: Map between McGraw Hill Construction Data and EIO Sectors

	IO Sectors				
McGraw Hill data (1997)	New residential 1-unit structures	New multifamily housing structures	Commercial and institutional buildings	Manufacturing and industrial buildings	
Space type	Sector 23011	Sector 23012	Sector 23021	Sector 23022	Total new construction starts
	1000 ft^2				
Stores and Restaurants			220,151		220,151
Warehouses (excl. manufacturer owned)				180,980	180,980
Office and Bank Buildings			178,570		178,570
Parking Garages and Automotive Services			109,611		109,611
Manufacturing Plants, Warehouses, Labs				146,835	146,835
Schools, Libraries, and Labs (nonmfg)			130,653		130,653
Hospitals and Other Health Treatment			66,488		66,488
Government Service Buildings			39,337		39,337
Religious Buildings			24,272		24,272
Amusement, Social and Recreational Bldgs			61,043		61,043
Miscellaneous Nonresidential Buildings			30,661		30,661
Hotels and Motels			86,821		86,821
Dormitories			10,624		10,624
One-family Houses	2,182,072				2,182,072

Two-family Houses		51,857			51,857
Apartments		351,505			351,505
Total new construction starts	2,182,072	403,362	958,231	327,815	3,871,480

Appendix C: Map from Handbook of Energy Use for Building Construction to EIO Sectors

Embodied and on-site ("direct") energy for construction of buildings (Adapted from Stein et al 1981):

Handbook sector number	Building Type	Total embodied and direct energy	Total direct energy	Total new construction starts
		Btu/ft^2		1000 ft^2
23	Residential , one family	715,611	98,807	1,122,169
24	Residential, two family	635,638	112,825	55,708
25	Residential, garden apartments	664,482	129,906	227,787
26	Residential, high-rise apartments	744,703	157,802	160,225
27	Residential, alterations and additions	NA	NA	NA
28	Hotel and motel	1,145,337	259,533	61,187
29	Dormitories	1,466,399	358,974	40,426
30	Industrial buildings	983,697	108,108	476,468
31	Office buildings	1,667,111	381,768	157,578
32	Warehouses	566,071	84,457	103,468
33	Garages and service stations	788,024	167,691	41,801
34	Stores and restaurants	960,050	235,980	209,333
35	Religious buildings	1,273,540	267,570	54,564
36	Educational buildings	1,404,249	279,866	315,485
37	Hospital buildings	1,742,549	367,852	67,979
38	Other non-farm buildings	147,192	330,352	159,483
48	Farm residences	561,914	36,917	54,457
49	Farm service buildings	147,799	8,587	392,763

Map between Handbook sectors and EIO LCA sectors:

Stein et al (1981)		New residential 1-unit structures	New multifamily housing structures	Commercial and institutional buildings	Manufacturing and industrial buildings
		IO Sectors			
Handbook sector number	Building Type	Sector 23011	Sector 23012	Sector 23021	Sector 23022
23	Residential , one family	X			
24	Residential, two family		X		
25	Residential, garden apartments		X		
26	Residential, high-rise apartments		X		
27	Residential, alterations and additions*				
28	Hotel and motel			X	
29	Dormitories			X	
30	Industrial buildings				X
31	Office buildings			X	
32	Warehouses				X
33	Garages and service stations			X	
34	Stores and restaurants			X	
35	Religious buildings			X	
36	Educational buildings			X	
37	Hospital buildings			X	
38	Other non-farm				

	buildings*				
48	Farm residences*				
49	Farm service buildings*				
Total new construction (1000 ft^2)		1,122,169	443,720	948,353	579,936
Total embodied and direct energy (Billion Btu)		803,036	306,091	1,256,936	527,270
Total direct energy (Billion Btu)		110,878	61,160	274,858	60,249
Total embodied and direct energy intensity ($kBtu/ft^2$)		716	690	1325	909
Total direct energy ($kBtu/ft^2$)		98.8	138	290	104

* These sectors do not belong to the four EIO LCA sectors of this study.

Appendix D: Carbon storage for forest and grassland types

Instructions: Multiply dry mass by carbon fraction of 0.5

ABOVE-GROUND BIOMASS IN FORESTS

Domain	Ecological zone	Continent	Above-ground biomass (tonnes d.m. ha^{-1})
Tropical	Tropical rain forest	Africa	310 (130-510)
		North and South America	300 (120-400)
		Asia (continental)	280 (120-680)
		Asia (insular)	350 (280-520)
	Tropical moist deciduous forest	Africa	260 (160-430)
		North and South America	220 (210-280)
		Asia (continental)	180 (10-560)
		Asia (insular)	290
	Tropical dry forest	Africa	120 (120-130)
		North and South America	210 (200-410)
		Asia (continental)	130 (100-160)
		Asia (insular)	160
	Tropical shrubland	Africa	70 (20-200)
		North and South America	80 (40-90)
		Asia (continental)	60
		Asia (insular)	70
	Tropical mountain systems	Africa	40-190
		North and South America	60-230
		Asia (continental)	50-220
		Asia (insular)	50-360
Subtropical	Subtropical humid forest	North and South America	220 (210-280)
		Asia (continental)	180 (10-560)
		Asia (insular)	290
	Subtropical dry forest	Africa	140
		North and South America	210 (200-410)
		Asia (continental)	130 (100-160)
		Asia (insular)	160
	Subtropical steppe	Africa	70 (20-200)
		North and South America	80 (40-90)
		Asia (continental)	60
		Asia (insular)	70
	Subtropical mountain systems	Africa	50
		North and South America	60-230
		Asia (continental)	50-220
		Asia (insular)	50-360

ABOVE-GROUND BIOMASS IN FORESTS

Domain	Ecological zone	Continent	Above-ground biomass (tonnes d.m. ha^{-1})
Temperate	Temperate oceanic forest	Europe	120
		North America	660 (80-1200)
		New Zealand	360 (210-430)
		South America	180 (90-310)
	Temperate continental forest	Asia, Europe (≤20 y)	20
		Asia, Europe (>20 y)	120 (20-320)
		North and South America (≤20 y)	60 (10-130)
		North and South America (>20 y)	130 (50-200)
	Temperate mountain systems	Asia, Europe (≤20 y)	100 (20-180)
		Asia, Europe (>20 y)	130 (20-600)
		North and South America (≤20 y)	50 (20-110)
		North and South America (>20 y)	130 (40-280)
Boreal	Boreal coniferous forest	Asia, Europe, North America	10-90
	Boreal tundra woodland	Asia, Europe, North America (≤20 y)	3-4
		Asia, Europe, North America (>20 y)	15-20
	Boreal mountain systems	Asia, Europe, North America (≤20 y)	12-15
		Asia, Europe, North America (>20 y)	40-50

DEFAULT BIOMASS STOCKS PRESENT ON GRASSLAND , AFTER CONVERSION FROM OTHER LAND USE			
IPCC climate zone	**Peak above-ground biomass[1] (tonnes d.m. ha^{-1})**	**Total (above-ground and below-ground) non-woody biomass[2] (tonnes d.m. ha^{-1})**	**Error [3]**
Boreal – Dry & Wet[4]	1.7	8.5	± 75%
Cold Temperate – Dry	1.7	6.5	± 75%
Cold Temperate –Wet	2.4	13.6	± 75%
Warm Temperate – Dry	1.6	6.1	± 75%
Warm Temperate –Wet	2.7	13.5	± 75%
Tropical – Dry	2.3	8.7	± 75%
Tropical - Moist & Wet	6.2	16.1	± 75%

[1] Data for standing biomass are compiled from multi-year averages reported at grassland sites registered in the ORNL DAAC NPP database [http://www.daacsti.ornl.gov/NPP/].

[2] Total above-ground and below-ground biomass values are based on the peak above-ground biomass values, and the below-ground biomass to aboveground biomass ratios (Table 6.1).

[3] Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

[4] Due to limited data, dry and moist zones for the boreal temperature regime and moist and wet zones for the tropical temperature regime were combined.

massive amounts of data. Makers of Green Globes and CASBEE simplified the LCA process for their users by providing aggregate data specific to buildings.

3.2.1 Introduction to Life Cycle Assessment for buildings

Life cycle assessment examines the environmental impact of a product throughout its life, from production through disposal. An LCA for building projects would ideally do two major things. First, it would measure the environmental impacts of all aspects of a building project. Second, it would reveal to designers and other stakeholders where they can have direct influence on the mitigation of that impact. Figure 3-3 illustrates this concept. At this state of the science, it is not possible to directly account for all the ways designers can have influence. However, Green Globes and CASBEE are accounting for some ways. These two methods are described in the following sections.

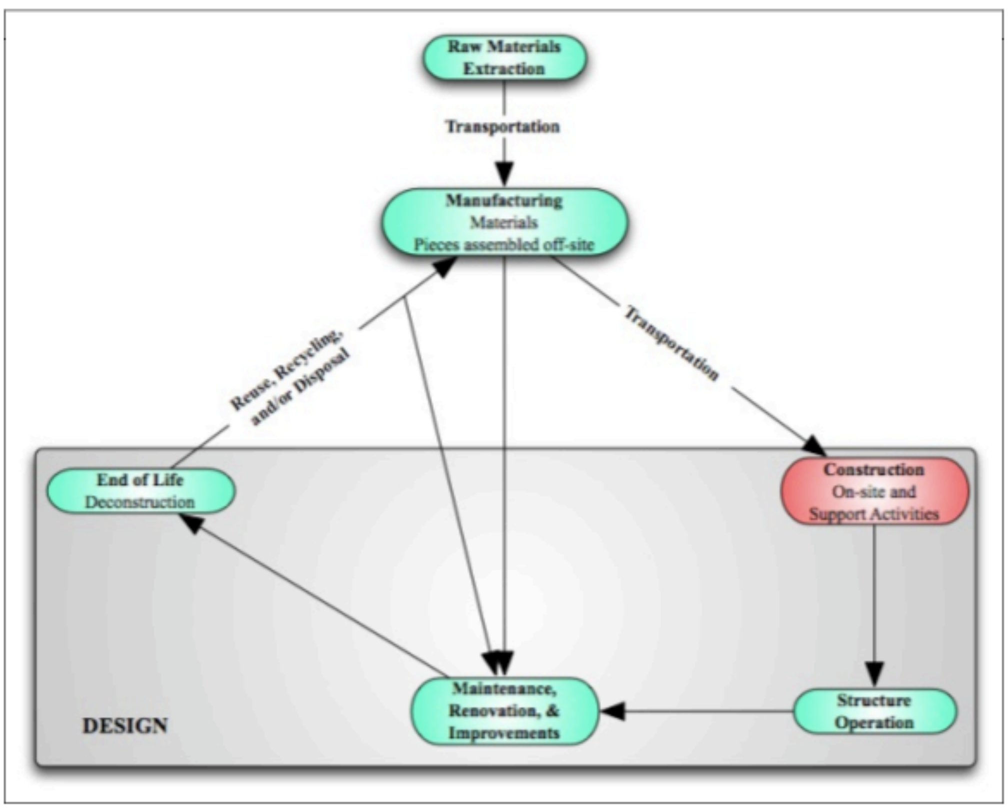

Table 3-3. Sources of environmental impact. Sources occur in different phases, from extraction of raw materials through operation and demolition. For most phases, designers and other stakeholders can have direct influence on that impact. (Image source: Sharrard 2007)

3.2.2 Green Globes

Canadian-based Green Building Institute's Green Globes rating system has partnered with the Athena Institute to include an optional LCA of building embodied energy.[15] A calculator, known as "EcoCalculator," was produced to estimate the carbon and other emissions embodied in entire building assemblies—not individual materials. User effort is therefore greatly reduced, as the only inputs are area and type of building assembly. Users are able to choose between different assemblies based on the embodied environmental impact.

In order to produce the estimates of assemblies, the developers of EcoCalculator built different assemblies in Athena's other calculator, the "ImpactEstimator." The ImpactEstimator calculator takes into account "resource extraction and processing; product manufacturing; on-site construction of assemblies; all related transportation; maintenance and replacement cycles over an assumed building service life; and structural system demolition and transportation to landfill."[16]

The underlying data for the ImpactEstimator was produced using process-based LCA. A process-based approach to LCA defines all the steps required to create and dispose of a product and estimates the environmental impact attributable to each step. NREL's US Life Cycle Inventory Database and Athena's own database use this type of data.

The EcoCalculator presents several alternative building assemblies and their associated emissions estimated on a per square foot basis. For instance, one interior wall assembly may consist of 2x4 wood studs 24" on-center, 5/8" gypsum board, and two coats of latex paint. Another interior wall assembly may have 2x6 wood studs that are 16" on-center, etc. The average impact of all these

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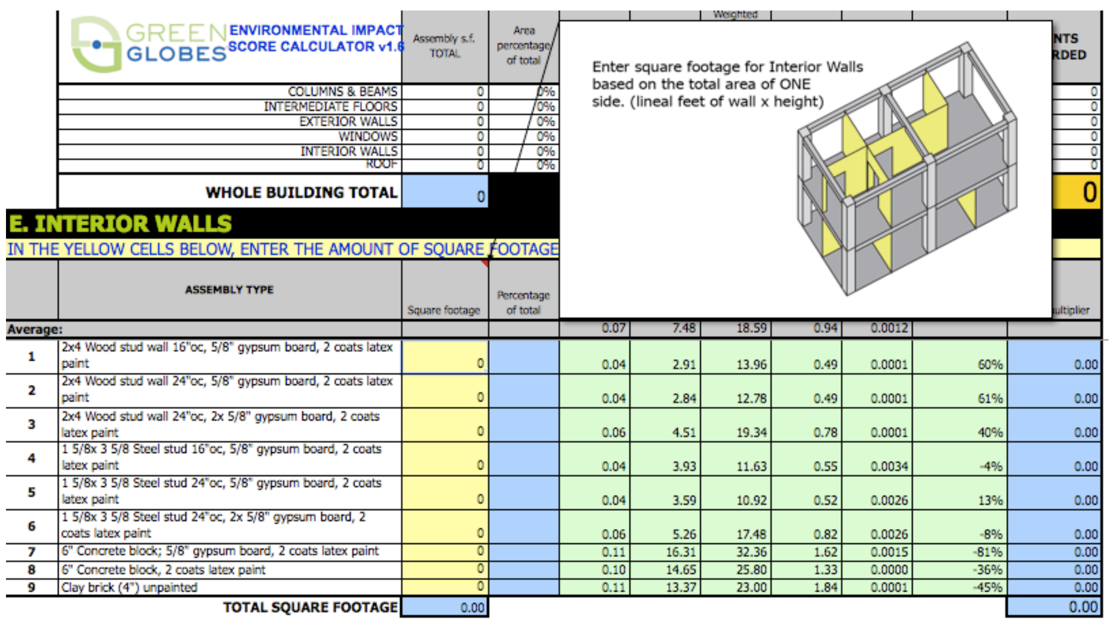
[15] The Green Building Institute (accessed October 2008) http://www.thegbi.org/green-globes-tools/
[16] Athena Institute (accessed October 2008) http://www.athenasmi.org/tools/ecoCalculator/

assemblies is calculated and compared to the selected assembly. A final score for this LCA section of the assessment system is calculated based on how the chosen assemblies compare to the average. Users can select assemblies and obtain instantaneous feedback as to whether or not the carbon emissions embodied in the assembly is below or above average.



	Assembly s.f. TOTAL	Area percentage of total
COLUMNS & BEAMS	0	0%
INTERMEDIATE FLOORS	0	0%
EXTERIOR WALLS	0	0%
WINDOWS	0	0%
INTERIOR WALLS	0	0%
ROOF	0	0%
WHOLE BUILDING TOTAL	0	

E. INTERIOR WALLS

IN THE YELLOW CELLS BELOW, ENTER THE AMOUNT OF SQUARE FOOTAGE

	ASSEMBLY TYPE	Square footage	Percentage of total							ultiplier
Average:				0.07	7.48	18.59	0.94	0.0012		
1	2x4 Wood stud wall 16"oc, 5/8" gypsum board, 2 coats latex paint	0		0.04	2.91	13.96	0.49	0.0001	60%	0.00
2	2x4 Wood stud wall 24"oc, 5/8" gypsum board, 2 coats latex paint	0		0.04	2.84	12.78	0.49	0.0001	61%	0.00
3	2x4 Wood stud wall 24"oc, 2x 5/8" gypsum board, 2 coats latex paint	0		0.06	4.51	19.34	0.78	0.0001	40%	0.00
4	1 5/8x 3 5/8 Steel stud 16"oc, 5/8" gypsum board, 2 coats latex paint	0		0.04	3.93	11.63	0.55	0.0034	-4%	0.00
5	1 5/8x 3 5/8 Steel stud 24"oc, 5/8" gypsum board, 2 coats latex paint	0		0.04	3.59	10.92	0.52	0.0026	13%	0.00
6	1 5/8x 3 5/8 Steel stud 24"oc, 2x 5/8" gypsum board, 2 coats latex paint	0		0.06	5.26	17.48	0.82	0.0026	-8%	0.00
7	6" Concrete block; 5/8" gypsum board, 2 coats latex paint	0		0.11	16.31	32.36	1.62	0.0015	-81%	0.00
8	6" Concrete block, 2 coats latex paint	0		0.10	14.65	25.80	1.33	0.0000	-36%	0.00
9	Clay brick (4") unpainted	0		0.11	13.37	23.00	1.84	0.0001	-45%	0.00
	TOTAL SQUARE FOOTAGE	0.00								0.00

Table 3-4. The Green Globes rating system offers an excel-based tool that is relatively fast and easy to estimate the embodied energy and environmental impact of buildings.

3.2.3 CASBEE

The Japan Green Build Council and Japan Sustainable Building Consortium have jointly release a 2008 version of CASBEE (Comprehensive Assessment System for Building Environmental Efficiency). Just prior to its release, the author of this thesis was able to personally interview a member of the research committee in Tokyo as part of a National Science Foundation research fellowship. The interview revealed that the major change from the 2006 edition was an explicit reference to global warming (a category entitled "Consideration of Global Warming") that includes a mandatory LCA of the project (Endo 2008). There are two major differences between this LCA and the one in Green Globes. First of all, the boundary of analysis is larger. Second, users must compare their building to the national average (CASBEE 2008).

The embodied carbon emissions data was produced using an Economic Input-Output (EIO) LCA approach (Endo 2008), which allows for a larger boundary of analysis than the process-based approach used by Green Globes, as shown by Table 3-1. EIO LCA estimates the environmental impact of each economic sector per dollar of input and uses an economic input-output table to determine the economic inputs required by a certain product (Sharrard 2007). In this way it provides an economy-wide assessment of environmental impact attributable to a product, while the process model is limited by the amount of steps that are included in the assessment. The Architectural Institute of Japan (AIJ) produced the embodied carbon emissions data from the 1995 Industrial Input-Output Table (CASBEE 2008).